WADC TECHNICAL REPORT 58-399
ASTIA DOCUMENT NO. AD 207780

VISION IN MILITARY AVIATION

JOSEPH W. WULFECK
ALEXANDER WEISZ
MARGARET W. RABEN
THE INSTITUTE FOR APPLIED EXPERIMENTAL PSYCHOLOGY
TUFTS UNIVERSITY
IN COOPERATION WITH
JACKSON & MORELAND, INC., ENGINEERS
WITH CONTRIBUTIONS BY
COL. GEORGE O. EMERSON
AERO MEDICAL LABORATORY

NOVEMBER 1958

CONTRACT NO. AF 33(616)-2906

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

WADC TECHNICAL REPORT 58-[illegible]
ASTIA DOCUMENT NO. AD 207[illegible]

VISION IN MILITARY AVIATION

JOSEPH W. WULFECK, PROJECT DIRECTOR
ALEXANDER WEISZ, PRINCIPAL INVESTIGATOR
MARGARET W. RABEN, PRINCIPAL INVESTIGATOR
THE INSTITUTE FOR APPLIED EXPERIMENTAL PSYCHOLOGY
TUFTS UNIVERSITY
IN COOPERATION WITH
JACKSON & MORELAND, INC., ENGINEERS
WITH CONTRIBUTIONS BY
COL. GEORGE O. EMERSON
AERO MEDICAL LABORATORY

NOVEMBER 1958

CONTRACT No. A[illegible] 33(6[illegible])-2906
PROJECT No. [illegible]
TASK No. 7[illegible]

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This report was prepared by Jackson and Moreland, Inc., and subcontractor, Tufts College, on Contract No. AF 33(616)-2906, under Project No. 7157, "Improving Visual Efficiency in Flying," Task No. 71808, "Physiology of the Eye." The work was administered under the direction of the Vision Section, Physiology Branch, Aero Medical Laboratory, Wright Air Development Center, with Col. George O. Emerson, USAF (MC), acting as contract monitor.

The compilers wish to thank the following persons for their assistance: Dr. H. Richard Blackwell, Dr. John H. Taylor, Dr. Jesse Orlansky, and Mr. Charles L. Collins. In addition, the contributions of the Human Engineering Information and Analysis Project to the bibliographical material used in this report and the cooperation of the many journals, publishers, societies, institutions, corporations, and government agencies who permitted the use of text, data, and illustrations originated by them are greatly appreciated.

The titles of all references contained in this report are UNCLASSIFIED.

ABSTRACT

The requirements of vision in military aviation are analyzed in the light of the human observer. Practical problems of perception encountered in many phases of flying are analyzed and discussed. A comprehensive bibliography is included in each section of the report for those who are interested in a more detailed approach to a particular subject.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Andres I. Karstens

ANDRES I. KARSTENS
Colonel, USAF (MC)
Ass't. Chief, Aero Medical Laboratory
Directorate of Laboratories

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont)

TABLE OF CONTENTS (Cont)

TABLE OF CONTENTS (Cont)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont)

LIST OF ILLUSTRATIONS (Cont)

LIST OF ILLUSTRATIONS (Cont)

LIST OF ILLUSTRATIONS (Cont)

LIST OF ILLUSTRATIONS (Cont)

LIST OF ILLUSTRATIONS (Cont)

LIST OF TABLES

CHAPTER 1

INTRODUCTION

This chapter is provided to clarify the purpose of the book, to introduce the reader to vision as a sensing device in military aviation, and to describe the way in which the text is organized.

PURPOSE OF THIS REPORT

The purpose of this report is to describe the capabilities and limitations of vision as a means of sensing and interpreting during many phases of military aviation.

This text is intended to be useful to aircraft designers, air tacticians, air crewmen, and to those performing visual examinations in the Air Force. A fairly comprehensive bibliography is presented for those engaged in basic and applied visual research in Air Force problems.

Vision is the sensing by a sense organ, the eye, of spatially discrete variations in brightness and/or hue, and the interpretation of these variations by the brain.

VISION FOR SENSING AND INTERPRETING

Vision then occurs essentially in two stages, the first at the eye, the second at the brain. At the eye, vision consists of the reception and photochemical change of electromagnetic waves within a narrow band of wave lengths with the result that impulses in the nervous system are initiated. At the brain, vision consists of interpretation of the nerve impulses reaching it through the visual system.

The eye is sensitive to changes in intensity of the electromagnetic waves it receives but, in order for the individual to respond to the electromagnetic waves, they must be above a certain minimum intensity, the absolute threshold for intensity. In order to respond to differences among intensities, the differences must also exceed a certain minimal value, the difference threshold for intensity. The eye is also sensitive to differences in wave length. In order for the individual to respond to electromagnetic waves, they must be within the narrow band to which the eye is sensitive and they must be above the absolute threshold for intensity. In order to respond to differences in wave length the differences must exceed the difference threshold for wave length.

Since the eye is sensitive to differences in intensity and wave length and since different objects and parts of objects emit or reflect waves of different intensity and wave length, the eye makes possible the first step in differentiating the shapes, sizes, locations, and movements of objects.

The second stage of vision occurs in the brain, which interprets the nerve impulses that reach it as a result of photochemical and neural events at the eye. The brain's function is part of the visual process, and without it there would be no vision. The simplest interpretation the visual part of the brain can make is that electromagnetic waves received by the eye are within the proper wave length band and have exceeded the absolute or difference threshold. In this case the object emitting the waves would be said to be visible. Such simple discriminations are said to be made at the sensory level and are called sensations.

The brain can make much more complicated interpretations beyond the sensory level. For example, it can combine sensations elicited by an object with learning or memory to make possible form recognition, color identification, and other complex events said to occur at the perceptual level and called perceptions. When an object is recognized or identified it is said to be perceptible.

Manuscript copy of this report was submitted to the Aero Medical Laboratory in May 1958 for publication as a WADC Technical Report.

Following perception a decision may be made as to what to do about the object that has been perceived. A response may be initiated if one seems to be required -- a series of nerve impulses to the muscles of the arms to move the control stick, for example. While decision and motor response are not part of the visual process, they are essential considerations in evaluating the visual system's effectiveness as a sensing and interpreting instrument, because only through them can the visual system's unusual sensitivity and acuity be fully utilized.

The object of the visual sciences is to determine, quantitatively where possible, the response characteristics of the human visual system to stimuli of given characteristics, or to find out what characteristics of a stimulus produce a given response. The response may be measured in many ways. It may be measured in terms of chemical or electrical activity of the eye produced by radiant energy, in terms of the sensations produced, in terms of perceptions produced or in terms of a muscular response of the observer to a visual stimulus.

It will be seen that no matter how it is measured, visual response is not a simple or linear function of the characteristics of the stimulus. Even at the simplest sensory level (the intensity threshold, for example), it is nonlinearly related to many parameters of the stimulus and of the observer: stimulus size, shape, location, wave length, distance, duration of exposure and observer's physical condition, past exposure to light, attention and others. The consequence of such complex, nonlinear relations is that one cannot make simple statements such as that an airplane in the sky will be seen twice as clearly if it is made to omit twice as much radiant energy in the visible spectrum as it will if its distance from an observer is halved. Visual research which can be applied to problems in military aviation cannot be conducted only by purely physical measurement of, for example wave length and intensity or by anatomical or physiological studies alone (though results of such research provide a basic part of all visual research). Instead, human observers are used to determine the visual system's response to the physical manipulation of the characteristics of the stimulus. Most of the studies cited in this publication were carried out by this method, called the psychophysical method.

It should also be remembered that vision is a subjective affair since it often involves complex functions such as attention and perception. It cannot be measured directly, like the characteristics of a vacuum tube. Therefore, visual performance must be measured in terms of characteristics of the object seen. For example, visual acuity, the ability to see detail, is sometimes measured in terms of the angle subtended by the smallest object that the viewer reports he can see. One can plot a curve of visual acuity in minutes of arc (or the reciprocal) versus some physical variables, such as wave length, energy, or time of exposure at a given illumination.

In military aviation the visual stimulus can be anything inside or outside the aircraft -- an enemy aircraft, an instrument on the panel, a runway or a runway marker, a bombing target, a navigational checkpoint, a warning light, a pip on a radar scope, a running light, or some simple or complex pattern of such items. It can be something that interferes with visual performance as well as something that aids it.

In considering visual requirements in military aviation, however, it is necessary to estimate the comparative importance of the various requirements. Therefore it is necessary to describe the criteria used in estimating their importance.

As far as can be forecast, manned aircraft will continue to be designed so that some visual sensing of the environment inside and outside the aircraft will be necessary.

In assigning a quantitative value to the relative importance of a visual requirement, one may mean either of two things: (1) If the requirement can be met by some means other than vision (an auditory signal, for example, or a servo system not requiring a human operator), then the importance of meeting the visual requirement must be weighted against the difficulties that would be encountered in substituting a nonvisual method, (2) When there is no practical substitute for vision, the importance then relates to the attention that should be given to improving visual performance in an essential function.

In military aviation, the attention (or effort in improvement) merited by a visual performance will be proportional to the improvement in combat effectiveness obtained by this effort and inversely proportional to the amount of effort necessary to obtain the improvement. By these criteria of im-

portance, there are some areas in military aviation wherein vision merits great attention and other areas wherein it merits little attention. An example of a most important area is locating a target. The word "locating" as used here includes detection and identification. If the target is located, and the weapon is transported successfully to the target, the weapon usually destroys the target that it was designed to destroy. However, locating the target is one phase of the combat mission that depends directly on the visual performances of detection and interpretation, and in this there is great variability of success.

Locating the target and transporting the weapon to the target are each essential phases of the combat mission. Therefore, the probability of locating the target times the probability of transporting the weapon to the target is equal to the probability of destruction of the target. This is shown in an equation: $Plt \times Ptw = Pdt$. For example, if there is a 50 percent probability of locating the target and a 50 percent probability of transporting the weapon to the target if it is located, the probability of destruction of the target is 25 percent (i.e., $50\% \times 50\% = 25\%$). Now if an improvement to 70 percent is achieved in transporting the weapon, the probability of target destruction, or combat effectiveness, is increased to 35 percent (i.e., $50\% \times 70\% = 35\%$). If instead, an improvement of 70 percent is achieved in locating the target, the probability of target destruction is again increased to 35 percent.

As seen from this equation, locating the target and transporting the weapon to the target are of equal value in influencing combat effectiveness. The aircraft is a vehicle for transporting the weapon. It transports the weapon to the target more expeditiously than any other vehicle. This is the reason for its ascendency in warfare. Billions of dollars have been spent in improving this transporting ability. It is evident from the foregoing equation that an equal percentage of improvement in locating the target would be equally rewarding in increased combat effectiveness. Locating the target is achieved with a rather low order of success for air targets and for small ground targets. The development of electronics is improving the detection phase for present day air targets. Electronically locating and identifying small ground targets is more difficult.

Contrast the importance of locating the target with the importance of some visual performance whose failure will not cause a combat mission to fail (nor cause an aircraft accident). This kind of visual performance has a comparatively insignificant effect on combat effectiveness.

For example, on a training mission the misinterpretation of an instrument or a mistake in reading a chart, while it may result in a navigational error, has little influence on combat effectiveness. Failure of a visual performance on a training mission influences combat effectiveness only if the failure of the visual performance results in failure of a training mission in whole or in part.

For military aviation, the visual requirements for combat conditions should be considered ahead of the requirements for training conditions. For example, cockpit illumination may be permitted to be high under training conditions, because here the crewman ordinarily does not need to be adapted to a level lower than necessary to see distant lights. However, under combat conditions, the crewman may need very low cockpit illumination so that he will be dark-adapted for the detection of blacked-out air and ground objects. Again, training and combat conditions differ in the visual requirements for cathode-ray tube displays versus direct vision in the observation of air objects. As a result of jamming techniques, electronically mediated target observation often loses in combat the capabilities that it has in training conditions. When this capability is lost, visual requirements for direct target observation may supplant those for cathode-ray tube observation.

ARRANGEMENT AND OBJECTIVES OF THIS PUBLICATION

It is basic to the purpose of this publication that engineers, tacticians, and others concerned with the design and use of aircraft and aircraft equipment should be able to apply visual data to new designs and new problems as they arise. To do so, they must have a knowledge of the principles of

vision -- the measurement of light, the physiology and optics of the eye, how psychophysical tests are made, and the various kinds of visual performance and how they are measured. These subjects, together with basic curves and data on the eye's performance, are presented in Chapters 2 through 8. In Chapter 8, in addition to a discussion of visual capacities and their measurement, some examples are given of how an engineer can manipulate physical variables to insure improved visual performance by pilot and aircrew. This chapter serves, then, as a bridge for the reader to the succeeding chapters, which deal with visual problems in specific aspects of flight. In preparing Chapters 9 through 15, the problem arose as to what categories military flight should be divided into for the most logical and least repetitive analysis of visual problems. In any flight, there are take-off, climbout, navigation, the mission -- transport, interception, bombardment, reconnaissance, or search -- and finally, letdown and landing. However, when the role of vision is examined in each flight phase, as in Table 1.1, it is found that in many respects it does not vary to any great extent from one phase to another.

Table 1.1 Visual Indications and Types of Visual Performance in Various Flight Missions

Information Required in Various Phases of Flight*	Type of Visual Indication	Visual Functions Required
1. Take-off and landing		
Spatial orientation Runway direction Attitude with respect to runway	Observation through windshield and/or of instrument panel	Space perception Brightness discrim. and
Engine condition	Instrument panel, controls	Visual acuity
2. Navigation and transport		
Bearing, distance and course relative to base and destination	Observation through windshield and/or by radar and maps	Space perception Brightness discrim. and
Altitude Speed	Instrument panel	Visual acuity
Weather	(Radio)	(Auditory discrim.)
3. Interception and bombardment		
Identity and position (angle, azimuth, and range) of other aircraft or ground target	Observation through windshield and/or by radar	Space perception Brightness discrim. and
Firing point	Computer	Visual acuity
Breakaway point	Radar and maps	
Position relative to base		
4. Reconnaissance and search		
Identity and position (bearing and distance relative to base) of target	Observation through windshield and/or by radar and maps	Space perception Brightness discrim. and Visual acuity

*The presentation of data is after pp. 49-50 of a report prepared by Dunlap & Associates, Inc. for Douglas Aircraft Company, El Segundo, California, December 10, 1954. The program was conducted under the joint auspices of the Bureau of Aeronautics and the Office of Naval Research.[1-1]

The chief differences are between (1) the use of direct vision (including vision with optical aids, such as binoculars) outside the aircraft to determine the aircraft's attitude and position relative to the ground and other objects, and (2) the use of vision to read instruments, for an indirect determination of attitude and position. Therefore, Chapters 9 through 15 analyze the problems of vision outside the aircraft first and then the problems associated with vision within the aircraft. We do not of course mean to imply that visual flight and instrument flight are altogether separate. On the clearest day, the pilot at high altitude has his head inside the cockpit a great deal of the time. In any aircraft, precise control of heading, airspeed, and altitude require instruments, no matter how much of the external world is visible. Furthermore, shifting vision from outside the aircraft to the instrument panel and back brings up special problems of adaptation and orientation. Nevertheless, the problems of outside vision and reading instruments lend themselves well to separate analysis. Within these broad categories, the problems found in specific phases of flight and in special types of operation are analyzed.

It can be seen that both the characteristics of the visual stimuli and the actual or desired responses of pilot and crew are often variable, complicated, and difficult to analyze. For this reason, and because the visual sciences are still in an early stage of development, little research has been done on some aspects of vision in military aviation, and indeed many of the problems have been poorly defined; there is little information on the visual requirements in many flight operations or the degree of accuracy with which pilot and crew must use their vision to perform crucial tasks. In such cases, the authors have drawn on whatever information is available, including interviews with pilots and others who have had experience in the problems. They have taken pains to point out areas where further research will be useful, and it is their hope that this book will prove useful as a guide to what should be done as well as to what has been done in basic research, field studies, and analyses of military requirements. Even when not immediately applicable, the discussions as they exist in the book may help in two ways: (1) by indicating parameters that should be studied or varied in a particular problem, and (2) by suggesting economical tests which might provide operationally valid information. This is intended to extend the usefulness of the book by indicating how it can be used as an adjunct in a systematic plan of action for design problems.

LIST OF REFERENCES

1-1 Dunlap and Associates, Inc., A report prepared for Douglas Aircraft Company, El Segundo, Calif. December 10, 1954. (CONFIDENTIAL)

GENERAL BIBLIOGRAPHY

1-2 Anon. Annotated Bibliography on Human Factors in Engineering Design. U. S. Navy, BuMed & Surg. February 1946. (CONFIDENTIAL)

1-3 Anon. Handbook of Human Engineering Data for Design Engineers Tech. Report No. SDC 199-1-1. Office of Naval Research, Special Devices Center. December 1, 1949. Prepared by Tufts College.

1-4 Anon. Physiology of Flight: Human Factors in the Operation of Military Aircraft. U. S. Army Air Forces, Air Technical Service Command, Engineering Division, Aero Medical Laboratory. March 15, 1945.

1-5 Anon. Services Available. U. S. Army Medical Library. January 1951.

1-6 Armstrong, Richard C., Visual Problems in Flying. U. S. Army Air Forces, Materiel Center, Experimental Engineering Section. August 19, 1942.

1-7 Bartlett, F. C., Principles of Synthetic Equipment and Training. 1950.

1-8 Brown, J. L., and Diamond, A. L., "A Device for Simulating the Visual Displays of PPI Scopes." J. Opt. Soc. Amer. Vol. 43. December 1953. pp. 1143-1146.

1-9 Chapanis, A., "How We See. A Summary of Basic Principles." Chapter 1 in Human Factors in Undersea Warfare. National Research Council, Washington, D. C. 1949.

1-10 Chapanis, A., Some Contributions of Experimental Psychology to Machine Design. Eighth Annual Time Study and Methods Conference Proceedings, Society for Advancement of Management, Inc., New York, N. Y. 1953.

1-11 Chapanis, A., Garner, W. R., and Morgan, C. T., Applied Experimental Psychology: Human Factors in Engineering Design. John Wiley and Sons, New York, N. Y. 1949.

1-12 Dunlap, Jack W., Human Problems in the Operation of High Speed Aircraft. Contract N6ori-151. Project No. 20-M-M-1b, Task Order No. 1. Office of Naval Research, Special Devices Center, New York, N. Y. August 1, 1947.

1-13 Fitts, Paul M., "Psychology and Aircraft Design: A Study of Factors Pertaining to Safety." Mechanical Engineering. February 1947. pp. 135-141 and 163.

1-14 Fulton, J. F., Hoff, P. M., and Perkins, H. T., A Bibliography of Visual Literature. 1939-1944, 1945.

1-15 Hick, W. E., Why the Human Operator? Medical Research Council, Applied Psychology Research Unit, APU 181/52. Psychological Laboratory, Cambridge, England. 1952.

1-16 Hodgman, Charles D., Handbook of Chemistry and Physics, Thirty-Sixth Edition. Chemical Rubber Publishing Company, Cleveland, Ohio.

1-17 Mead, Leonard C., "Application of Human Engineering to Flight Problems." J. Aviat. Med. Vol. 19. 1948. pp. 45-51.

1-18 Miles, Walter R., "Psychological Aspects of Military Aviation." Amer. Scientist. Vol. 33. July 1945. pp. 147-159.

1-19 Miles, Walter R., "Psychological Hazards for Flying Fighters." Science. Vol. 10. March 17, 1944.

1-20 Miller, Neal E., Psychological Research on Pilot Training. 1947.

1-21 Pecoraro, J. N., "The Use of an Operational Flight Trainer as a Research Tool for Aircraft Instrumentation and Cockpit Rearrangement." Aero. Engng. Rev. Vol. 13. No. 5. May 1954. pp. 86-93.

1-22 Pirenne, M. H., Vision and the Eye. Chapman and Hall Limited, London, England. 1948.

1-23 Rand, M. J., Young, W. F., Newkirk, R. F., and Noland, E. E., Industrial Research Laboratories of the United States, Including Consulting Research Laboratories, Ninth Edition. Bulletin of the National Research Council No. 1[illegible]. November 1950.

CHAPTER 2

THE NATURE AND MEASUREMENT OF LIGHT

Light is radiant energy that arouses visual sensations. It is limited to a narrow band of the radiant energy spectrum around 10^{-6} meters in wave length. The sensation of brightness is not a linear function of the amount of radiant energy received by the eye. Therefore, light is commonly measured by photometry, in which the eye itself is used as the sensing device, and the observer compares its brightness with that of a known standard. Photometric units are arbitrarily based on the international candle, which formerly was an actual candle and now is an incandescent filament of carefully maintained specification. Chief concepts and units are as follows: luminous flux, analogous to rate of transfer of energy (or quantity of illumination) measured in lumens (a point source of one international candle emits 4π lumens in all directions); intensity, the flux per solid angle from a point source, measured in candles; illuminance, the flux striking a surface, measured in lumens per unit of area; luminous emittance, the flux emitted in all directions from each unit of area of an extended source (including reflecting and transmitting sources), measured in lumens per unit of area; and luminance (brightness), the luminous emittance or reflectance in one direction from an extended source, measured in lumens per unit of area per steradian or in lamberts or millilamberts.

The sensation of color is most closely related to wave length of light, but it is also related to other physical properties of light, and it varies with the individual and the conditions of viewing. Usually a color is said to have three psychological components: hue (red, blue, orange, etc.), brightness, and saturation (the amount a color differs from a gray of the same brightness). Every hue in the spectrum may be matched by mixing two or three primary hues in a certain combination. In tristimulus color specification, a color is identified in terms of the proportionate reflectance or transmittance of each of the primary wave lengths that compose it. Standard values for comparison under three standard illuminants have been set up by the Commission Internationale de l'Eclairage. Color may also be specified by means of a color solid: Colors have been arranged in three dimensions for hue, value (brightness), and chroma (saturation); a sample of color may then be specified in terms of arbitrary numerical values in each dimension.

DEFINITION OF LIGHT

Light is defined as the aspects of radiant energy of which a human observer is aware through the visual sensations which arise from the stimulation of the retina of the eye. More simply put, light is visually evaluated radiant energy. Like other forms of radiant energy, such as radio and gamma rays, light travels through space at a constant velocity of 2.998×10^{10} cm/sec.

For some purposes, radiant energy may be considered as having a sinusoidal wave form. It stimulates vision only over a band of wave lengths 10^{-6} meters broad (Fig. 2.1). Within this band, the amplitude correlates roughly with the visual sensation of brightness and the wave length with the visual sensation of hue; the longest waves within the visible spectrum produce a sensation of red, and the shortest a sensation of violet. Notice that there is no place for white or black on the visible spectrum. According to physical definition, white is produced when all (visible) wave lengths are presented in equal amounts. Actually, the sensation of white may be produced when certain critical ones are presented together. The usual explanation for the sensation of white is that the eye cannot analyze the radiant energy that stimulates it. Thus, if the light covers a narrow band of wave lengths (monochromatic light), a particular hue is seen, but if it covers a wide range of wave lengths, with nearly equal energies at each length, the sensation of white is produced. Black, on the other hand, is usually treated as an absence of stimulation.

The wave length of light is expressed in microns (μ), equal to 10^{-6} meters, in millimicrons (mμ), equal to 10^{-9} meters, or in angstroms (A), equal to 10^{-10} meters. The red in Figure 2.1 could be designated either 0.7 μ, 700 mμ, or 7000 A.

PROPAGATION AND MEASUREMENT OF LIGHT

The eye is not a photographic plate; the intensity of a visual sensation depends not on the total amount of light transferred to the eye over a period of time, but on the rate of transfer beyond a

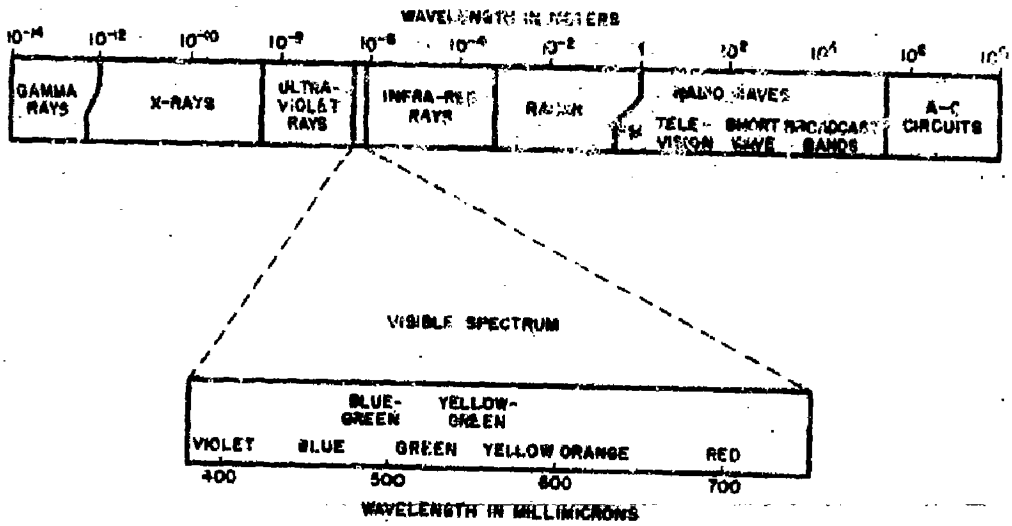


Figure 2.1 Visible Portion of the Radiant Energy Spectrum (after Chapanis2-1)

critical minimum duration. Therefore, magnitudes of light in photometry are given in terms of luminous flux (F), the time rate of flow of light.

While a number of different scales of photometric units are used, they are all expressions of the geometrical relations that exist in the propagation of luminous flux. The differences generally lie only in the amount of flux embraced by the units, much as the centimeter differs from the inch. Unfortunately, no single photometric scale of units has been accepted as a standard scale. Similarly, different investigators have used different names to describe the same aspect of light propagation. To avoid confusion, only one scale of units and only one system of nomenclature -- those that seem to the authors most logical and useful -- will be described in the paragraphs that follow. Other units and names will be listed and defined in tabular form.

Photometric units are derived from an arbitrary standard, the international candle. It was originally an actual sperm candle weighing 1/6 pound and burning at the rate of 120 grains of wax an hour. Now the primary standard is platinum at its melting point viewed through a small opening in an oven, which serves as a black body. The secondary standards are electric incandescent filaments maintained at the U. S. National Bureau of Standards.

In photometry, two kinds of light sources are important: a point source and an extended source.

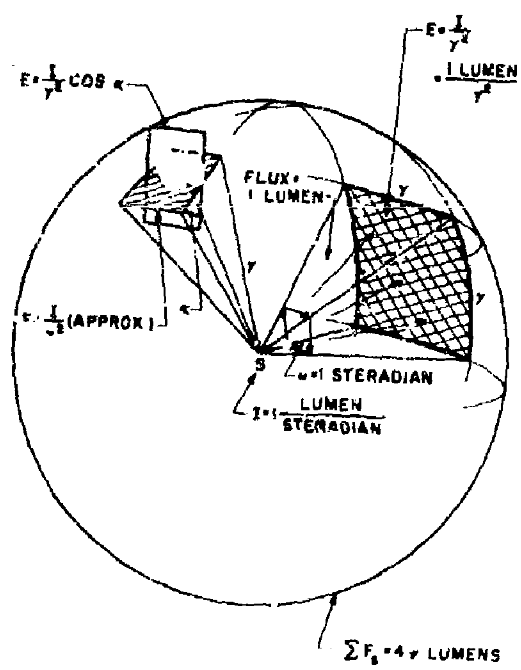


Figure 2.2 Relationships of Flux (F), Intensity (I), and Illuminance (E) About a Point Source Equivalent to 1 International Candle, Emitting Equally in all Directions

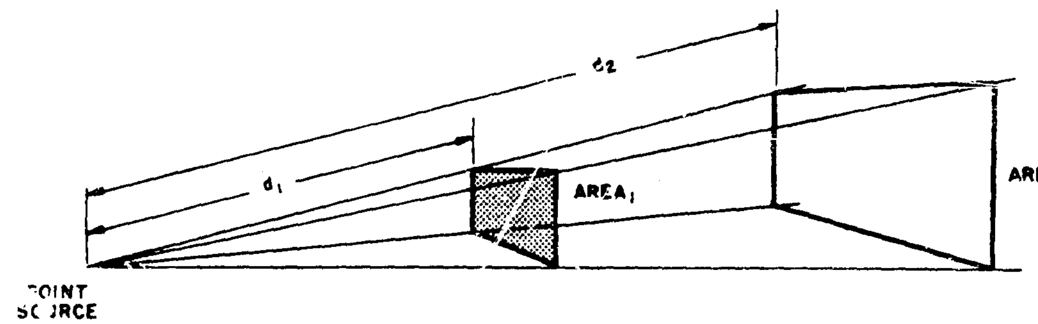
A point source is by definition infinitesimal, but a source of finite size may be considered a point source if it is small or distant enough so that the geometry of light emitted from it approaches that of light emitted from a point source. An extended source is by definition a source of finite size. In practice, it may be considered any source large enough so that the luminous flux emitted per unit of area is important. Note that when the word source is used, it need not be the ultimate source of light. The reflection of a distant light in the windshield may itself be considered a point source; a cloud transmitting and diffusing the light of the sun or a runway reflecting it may be considered an extended source. In fact, anything that can be seen is a source of light, because vision is (except in rare instances) stimulated only by light entering the eye.

Propagation of Light from a Point Source

The sum of all the light being emitted from a point source may be expressed geometrically as a solid. If light is emitted equally in all directions, the solid becomes a sphere. The geometrical relationships of light are shown in Figure 2.2. The basic unit of flux is the lumen. By definition, 1 lumen is equal to $1/4\pi$ times the total flux emitted by a point source equal to one international candle. (Since the visual investigator is usually concerned with the flux in a given direction rather than total flux, and since there is a total of 4π steradians of solid angle, ω, about a point, one lumen is defined as $1/4\pi$ total flux rather than total flux to facilitate mathematical manipulations.)

The flux emitted by a point source per unit of solid angle at a given radius is called intensity (I). Intensity is measured in lumens per steradian, and it can be seen that a point source equal to one international candle has an average intensity of 1 lumen per steradian.

The light striking a surface at some distance from a source is called illuminance (E) and is measured in lumens per square centimeter (or other unit of area). When the source of light is a point source, the illuminance on the surface is related to the intensity of the source by the law of inverse squares; that is, the area of a surface subtending a given solid angle increases with the square of its distance from the source. (See Fig. 2.3.) The concentration of flux falling on the surface must therefore decrease in proportion to the square of the distance. (If the surface is the retina



$$\frac{\text{LUMINOUS FLUX RECEIVED PER UNIT AREA}_1}{\text{LUMINOUS FLUX RECEIVED PER UNIT AREA}_2} = \frac{d_2^2}{d_1^2}$$

$$\frac{\text{AREA}_1}{\text{AREA}_2} = \frac{d_1^2}{d_2^2}\text{; THEREFORE}$$

$$\frac{\text{E AT AREA}_1}{\text{E AT AREA}_2} = \frac{\text{FLUX PER UNIT AREA}_1}{\text{FLUX PER UNIT AREA}_2} = \frac{d_2^2}{d_1^2}$$

Figure 2.3 Law of Inverse Squares

of the eye, the intensity of visual stimulation will also decrease with the square of the distance.) If the surface is the surface of a sphere whose center is a point source and whose radius is r, then each steradian of angle is subtended by an area r^2, and the illuminance, E, on the surface is found by

$$E = \frac{I}{r^2}$$

assuming that there is no absorption, reflection, or refraction of light between the source and the surface (Fig. 2.2). The same relation holds approximately true for a flat surface normal to the direction of light from a point source, provided that the surface subtends a small solid angle, so that its area approaches that of the spherical segment it subtends. If such a surface is tilted in respect to the direction of light, it can easily be shown that

$$E = \frac{I}{r^2} \cos \alpha$$

where α is the angle of tilt from the vertical (Fig. 2.2).

Refraction of Light

Light travels at different velocities in different media. When it passes from one medium to another at an angle, the light is refracted by an amount depending on the relative velocities and the angle of incidence (Fig. 2.4):

$$\frac{\sin \iota}{\sin \rho} = n = \frac{\text{Velocity in Medium A}}{\text{Velocity in Medium B}}$$

where

ι = angle of incidence

ρ = angle of refraction

n = refractive index of Medium A relative to Medium B when Medium A is air.

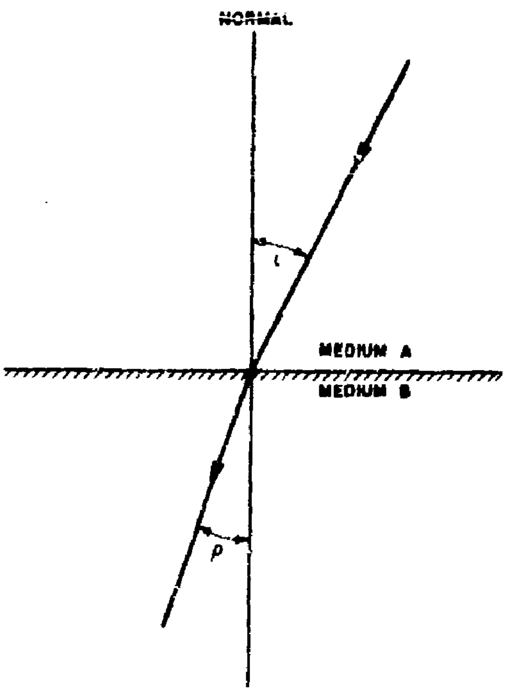


Figure 2.4 Refraction of Light

(It is assumed that the rays of light are not significantly out of parallel with each other.) It can be seen that if light is traveling at a higher velocity in the first medium than the second, $n > 1$, and $\rho < \iota$. Since light travels faster in air than it does in glass, plastics, and most other mediums, it can therefore be expected to bend toward the perpendicular when it passes from air to another medium. On passing from such a medium back to air, the light will be refracted equally in the opposite direction, so that it will resume traveling on its former course. However, the image, as seen by an observer on the opposite side of the medium from the light source, will be offset by an amount that is a function of the thickness of the medium as well as of $\sin \iota / \sin \rho$ (see Fig. 2.5). So, undesirable refractions may become an increasingly serious problem as windshields are made of thicker construction to withstand the higher aerodynamic loadings of high-performance aircraft, especially when the position

of nearby objects must be judged precisely as in taxiing.

Note that if the observer's eye is at the center of a spherical transparency, then the light reaching his eye from any point source outside the transparency will be normal to the transparency. That is, $\iota = 0$, $\sin \iota = 0$, and $\sin \iota / \sin \rho = 0$; thus, there is no refraction regardless of the refractive index or the thickness of the transparency.

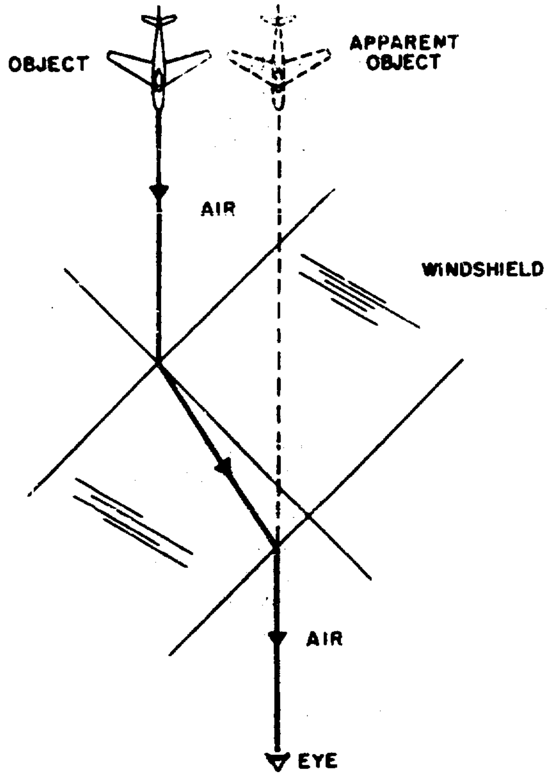


Figure 2.5 How Image is Offset When Light Passes From Air Through Another Medium and Back to Air

Reflection and Transmission

When luminous flux strikes an object, the object will reflect it, absorb it, transmit it, or more probably do some of each. When flux strikes a perfectly reflecting surface, such as a flawless mirror, at an angle, all the flux is reflected back at an equal angle; angle of incidence equals angle of reflection. Other reflecting surfaces scatter more or less of the flux; a coarse magnesium oxide or chalk-coated surface, for example, will scatter nearly all of it. A surface that scatters much of the flux is diffusing. One that scatters little is specular. With an imperfectly diffusing surface, angle of incidence equals angle of reflection for maximum flux.

The reflectance, or coefficient of reflection, of a surface is the ratio of flux reflected from a surface to flux striking the surface. The transmittance, or coefficient of transmission, of a medium is the ratio of flux leaving to flux entering. (This definition is often limited to homogeneous, isotropic, non-diffusing mediums.)

Propagation of Light from an Extended Source

When a surface transmits or reflects light, that surface may be considered an extended source of light (except in the special case of a perfectly reflecting or transmitting surface receiving light from a point source). Luminous emittance, L, is the name for flux emitted per unit of area of an extended source, and, like illuminance, it is measured in lumens per square centimeter. If the luminous emittance consists entirely of reflected light, then

$$\text{reflectance} = \frac{L}{E}.$$

If the luminous emittance consists entirely of transmitted light, then

$$\text{transmittance} = \frac{L}{E}.$$

However, the brightness of an extended source, as viewed from any given point, depends on the angle from which it is viewed and on the luminous flux emitted from each point on the surface per unit of solid angle.

Consider first a plane surface that emits light equally in all directions. If this surface were viewed from an angle, it would appear brighter than if viewed from straight ahead. The reason for this is indicated in Figure 2.6. All the flux emitted from the surface in any given direction must pass through an area equal to the projected area of the emitting surface. The greater the angle, the smaller the projected area; and since the same total flux is emitted in every direction, the flux will be more concentrated -- and the surface will appear brighter -- in inverse proportion to the size of the projected area. The size of the projected area, and hence the brightness, is proportional to the cosine of the viewing angle -- the angle between a line perpendicular to the emitting surface and the observer's line of sight.

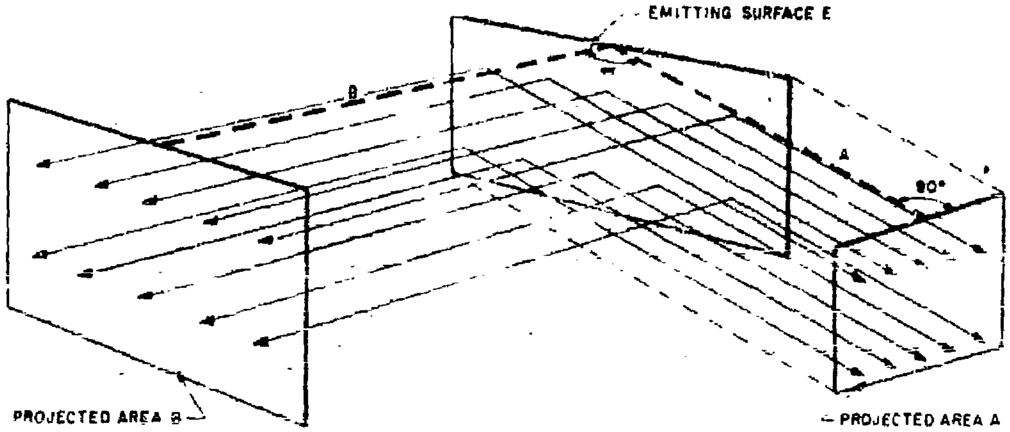


Figure 2.6 Area of an Emitting Surface (E) as Viewed Along Perpendicular (B) and Along (A) at Angle α From Perpendicular

In Figure 2.6, projected area B, being straight out from the emitting surface, is equal to it in area. Area A is smaller; Area A = Area B $\times \cos \alpha$. Flux per unit area at A = flux per unit area at B/$\cos \alpha$, assuming flux is emitted equally in all directions.

However, a diffusing surface usually emits or reflects the maximum amount of luminous flux straight outward, and the amount decreases as the angle from the perpendicular increases. If this decrease is exactly proportional to the cosine of the angle with the perpendicular, as illustrated by the vector diagram, Figure 2.7, it will just cancel out the increase in brightness due to the light's being concentrated in a smaller projected area. Such a surface will appear equally bright from any angle. It is said to follow the cosine law, and to be perfectly diffusing.

Luminance, L, is the luminous flux emitted per unit of solid angle per unit of area from an extended source. The visual sensation of brightness is thus a function of the luminance of the

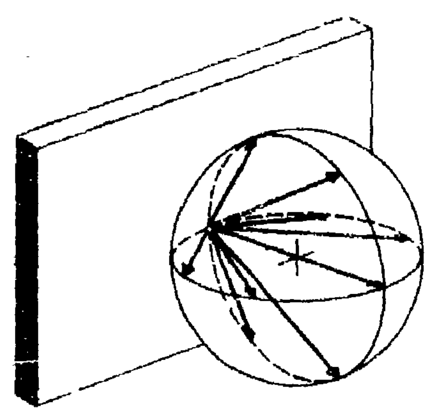


Figure 2.7 Reflection or Emission According to Cosine Law

Energy is transmitted in each direction at rate proportional to cosine of the angle with the perpendicular; vectors form a sphere.

source. Luminance is measured in lumens per steradian per square centimeter (or other unit of area), or more commonly in terms of a special unit called the lambert (L). For a perfectly diffusing surface, 1 lambert = $1/\pi$ lumens per steradian per square centimeter. Where the surface is not perfectly diffusing, its luminance as viewed from a given direction may still be expressed in terms of lamberts, by comparing it with a perfectly diffusing surface of known luminance. Since the lambert is an inconveniently large unit for most purposes, luminance is more often measured in millilamberts, mL (lamberts x 10^{-3}), in microlamberts, μL (lamberts x 10^{-6}), in micromillilamberts, μmL (lamberts x 10^{-9}), or in micromicrolamberts, $\mu\mu$L (lamberts x 10^{-12}).

An important property of a perfectly diffusing extended source is that within a limiting distance that depends on the size of the source, the luminance does not vary with the distance of the eye. It will be remembered that the flux reaching the eye from a point source decreases with the square of the distance of the eye from the source. The same decrease takes place in the flux emitted by any point on an extended source. This decrease is offset by the increase in the area from which the eye receives flux as it gets farther away. The situation is illustrated in Figure 2.8, where you will note the presence of an artificial pupil which serves to limit the visual field. What this means is that the apparent brightness of an extended source does not vary with distance to the eye for these conditions.

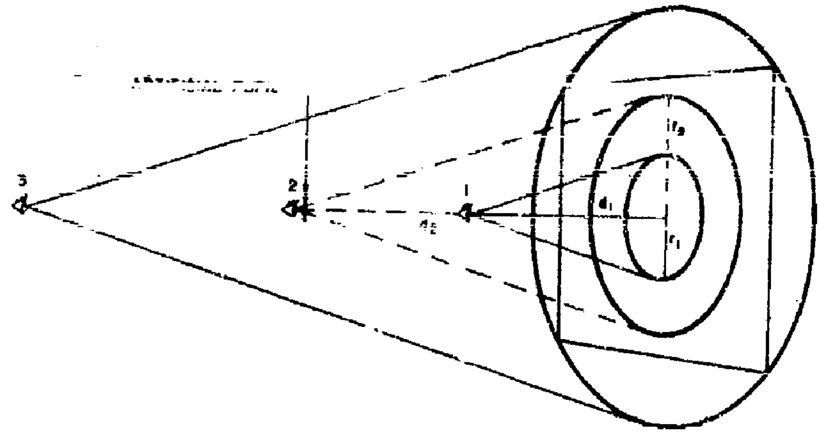


Figure 2.8 How the Luminance of an Extended Source is Independent of Distance up to a Certain Limit Imposed by the Size of the Source

Surfaces other than planes may be perfectly diffusing. The moon's surface is perfectly diffusing, or almost; it appears as bright at the edge, where the line of sight is tangential to its surface, as at the center, where it is viewed "head on."

When a reflecting surface is not perfectly diffusing, the maximum amount of light comes from it at an angle equal to the angle of incidence. There are now three variables -- the angle of incidence, the amount of diffusion, and the viewing angle -- and a special analysis is necessary in each case.

One further unit is used in some visual research to express stimulus intensities in terms of illuminance produced on the retina of the eye by a source. The eye responds to the flux that actually reaches the retina. This flux is controlled by (among other things) the amount the pupil is open (Chapter 3). A unit called the troland takes into account both the luminance of the source and the pupillary opening; one troland is the visual stimulation produced by a luminance of one lumen per steradian per square meter when the entrance pupil has an area of one square millimeter. Artificial pupils can be constructed for laboratory experiments, and the results expressed in trolands.

Other Photometric Units

Table 2.1 lists other photometric units often found in the results of visual research, and compares them with the units defined in the foregoing paragraphs. Figure 2.9 shows the relations of some of these units to each other and to a point source. Table 2.2 is a more detailed conversion table for units of luminance; it gives a quick means of comparing data presented in different units with each other or with the requirements of a problem in aircraft design or operation.

Table 2.1. Table of Equivalences for Commonly Used Photometric Units

Intensity (I)	1 lumen /steradian = 1 candle = 1 candle power
Illuminance (E)	lumens/cm^2 1 lumen/m^2 = 1 meter candle = 1 lux 1 lumen/ft^2 = 1 ft-candle (ft-c)
Luminous Emittance (L)	lumens/cm^2 lumens/m^2 lumens/ft^2
Luminance (B)	lumens/steradian/m^2 (or cm^2) lamberts (L) = millilamberts (mL) $\times 10^3$ = microlamberts (μL) $\times 10^6$ for a perfectly diffusing surface, 1 lambert = $1/\pi$ candles/cm^2 foot-lambert (ft-L) = 1.076 mL

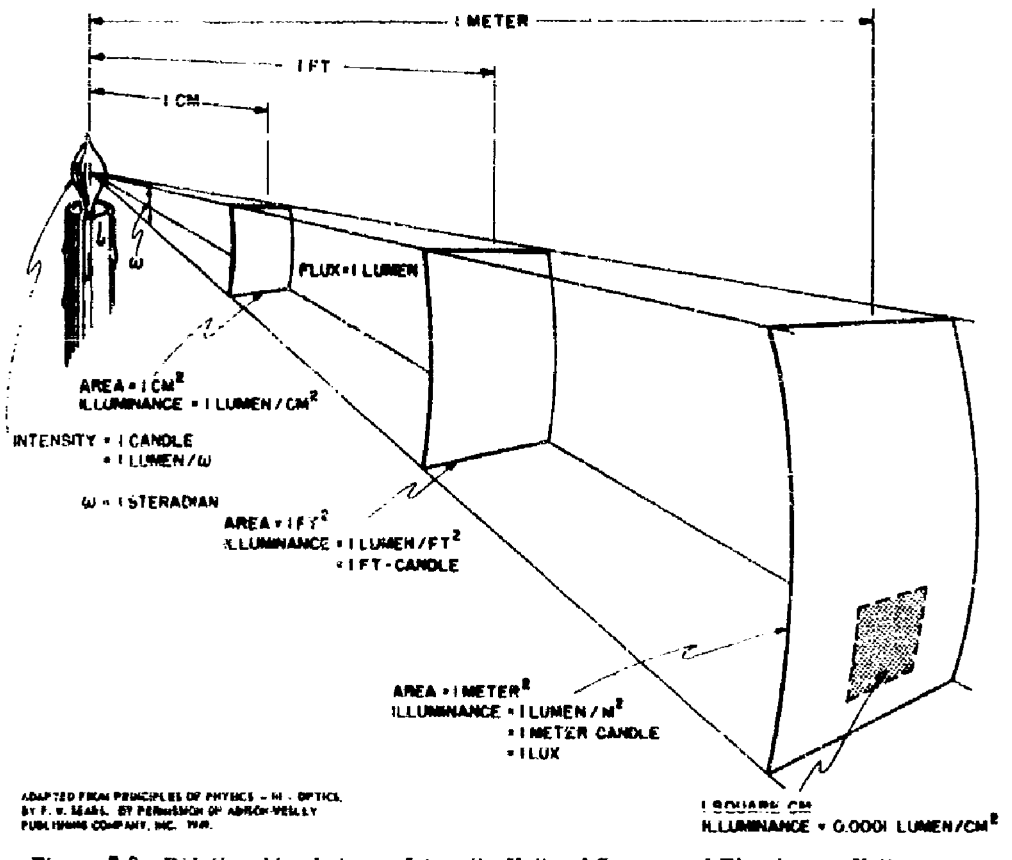
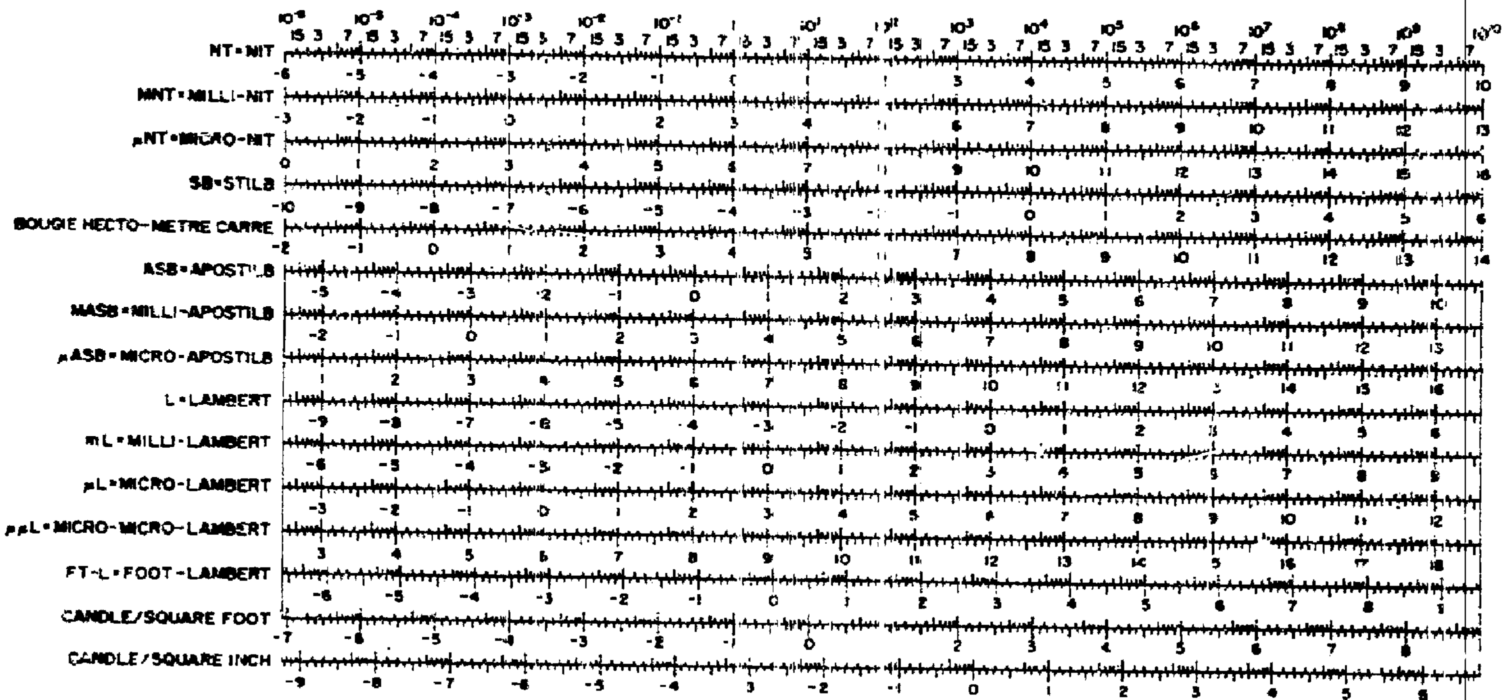


Figure 2.9 Relationships between Intensity Units of Source and Illuminance Units on Surfaces at Various Distances (after Sears[2-6])

Table 2.2 Nomograph of Equivalent Values of Commonly Used Units of Luminance. Below Each Bar Logarithmic Units and Their Subdivisions are Given. Above the Nit Bar Natural Figures and Subdivisions are Given. Above Each Bar Subdivisions for Natural Figures are Given. USAF School of Aviation Medicine - H. W. Rose



THE NATURE OF LUMINOUS FLUX

Since light is defined in terms of the eye's response to radiant energy, one would suspect that, while luminous flux is related to the transfer of radiant energy, the relation is neither linear nor simple. His suspicions would be correct. Three factors complicate the situation.

The first is the eye's differential response to wave lengths within the visible spectrum. Figure 2.10 shows that the eye is twice as sensitive to a yellow-green of 550 mμ, as it is to a blue of 450 mμ, and many times more sensitive to a yellow-green than to violet and red, at the ends of the visible spectrum. The situation is further complicated by differences in the responses of individuals. Figure 2.11 shows that some individuals of "normal vision" are only a fraction as sensitive to light at certain wave lengths as other individuals.

The second complicating factor is that the eye uses one set of receptors, the cones, for higher levels of illumination, and the more sensitive but less precise rods at low levels of illumination (see Chapter 3). At in-between levels, it uses both types of receptors to varying degrees. Rod vision is most sensitive to light at just over 500 mμ, while cone vision is most sensitive to light of a wave length some 50 mμ higher (Fig. 2.10). The two types of receptors also differ in the time it takes them to regain maximum sensitivity after their sensitivity has been impaired by exposure to bright light, and in other respects. Therefore, if radiant flux is increased or decreased so as to bring the level of illumination through the transition zone between rods and cones, the curve for sensation of brightness -- the luminance curve -- becomes displaced.

The third complicating factor is that even if wave lengths are held the same, and only rod or cone vision is used, the sensation of brightness does not increase linearly with the increase in radiant flux received at the eye. That is, doubling the watts of radiant flux does not produce a sensation of double the brightness.

For those reasons, the human eye was originally used as the sensing device in working out standard scales of photometric values, and human observers are generally used in determining the luminance of objects in laboratory and field tests; generally under each set of conditions, the observers compare an unknown light source with a standard source of known luminance or intensity. Similarly, devices used to measure light are designed, by filters or other means, to respond to radiant flux in the same manner as the eye.

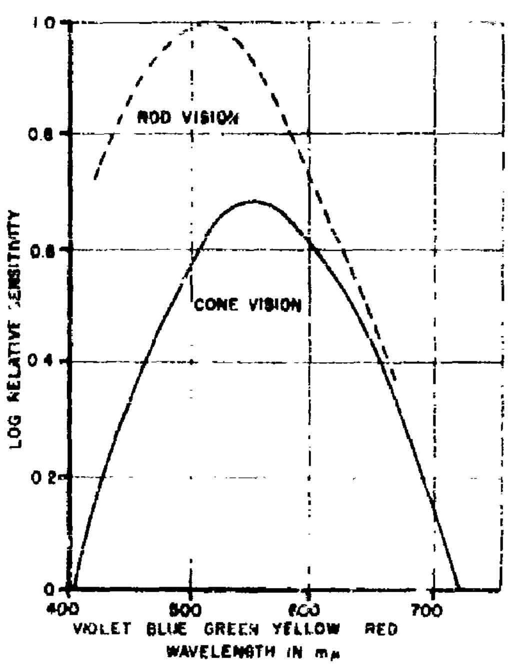


Figure 2.10 Standard Luminosity Curves: Relative Sensitivity to Radiant Flux as a Function of Wavelength
(data from Hecht and Williams2-4)

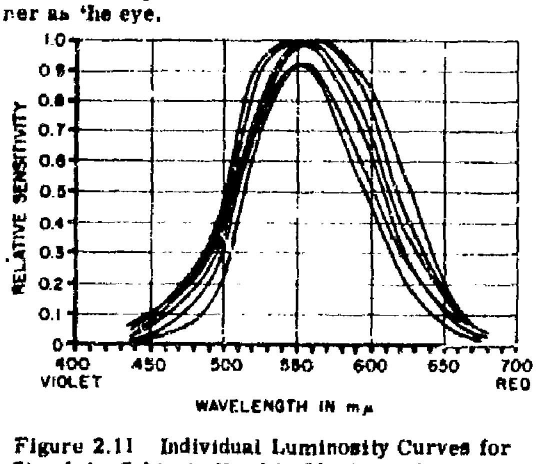


Figure 2.11 Individual Luminosity Curves for Six of the Subjects Used in Obtaining the Standard Luminosity Curves
(data from Gibson and Tyndall 2-2)

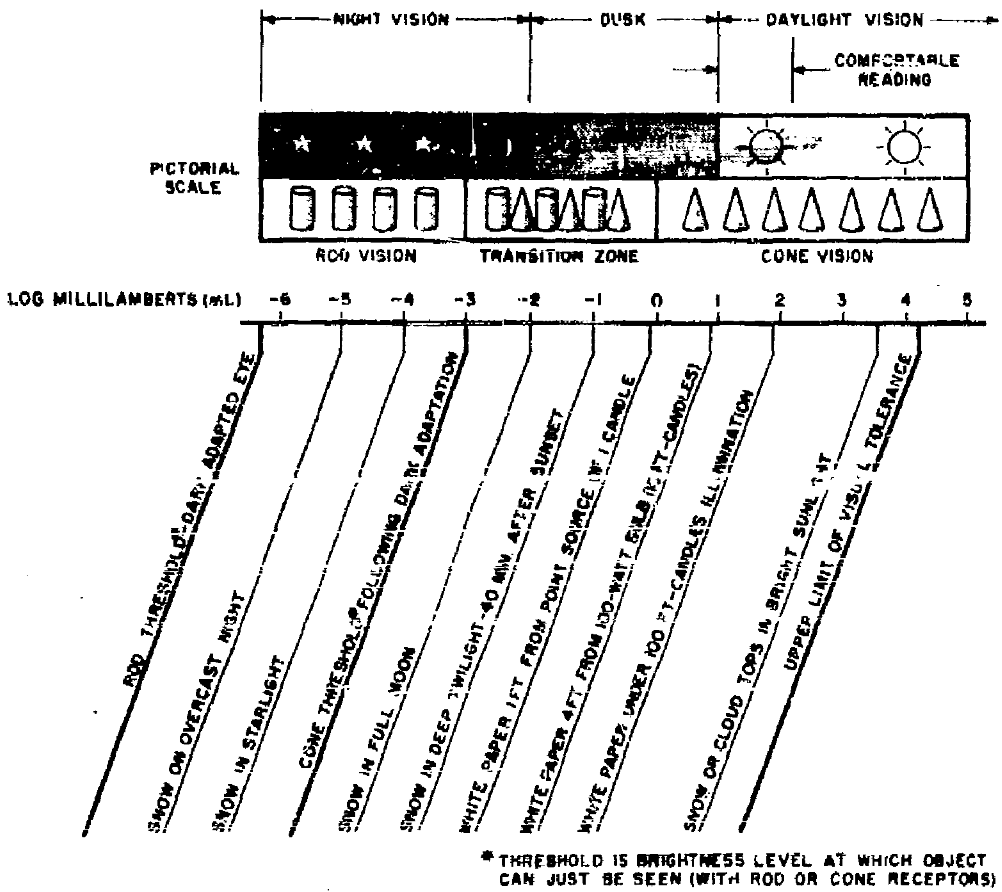


Figure 2.12 Luminance in Millilamberts Under Various Natural Conditions of Illumination

Values at which normal eye shifts from rod vision to combined rod-and-cone and full-cone vision are also shown.

The fact remains, however, that, under any given set of conditions, a given amount of luminous flux is produced by a given radiant flux that can be specified in terms of watts and spectral composition.

Figure 2.12 shows luminance values under natural conditions ranging from the minimum luminance that can be detected under the most favorable conditions to the highest luminance the eye can tolerate.

The sensation of color combines separate psychological components that are complexly related to different physical properties of light. It does not lend itself easily to psychophysical evaluation or photometric measurements; the psychological sensations themselves must be evaluated, and these are difficult to express in terms that mean the same thing to everyone. Nevertheless, a number of more or less successful methods have been developed for specifying color and relating it to the physical properties of light. The most important are described later in this chapter.

Color may be considered as having three psychological components: hue, saturation, and brightness. Most systems of color specification make use of these three concepts in one form or another.

Hue is the aspect of color commonly denoted by such names as red, yellow, green, blue, orange, and many others. The most closely related physical property of light is wave length -- though the hue purple does not correspond to any wave length in the spectrum.

Saturation is defined as the degree to which a sensation of hue differs from a gray of the same brightness. Colors that are 100 percent saturated are called spectrum colors. When white light is added to a spectrum color, the spectrum color decreases in saturation. For example, a spectrum red becomes more or less pink when it is mixed with white light; it is still red in hue, but its saturation has decreased.

The sensation of brightness is related to the amount of luminous flux reaching the eye from an object or light source. Other things being equal, a source of high intensity or luminance will seem bright-colored -- bright red, bright blue, etc. -- while a source of low intensity or luminance will seem dark- or dull-colored. A sample of red that seems dark on a cloudy day will seem bright on a sunny day; the hue and saturation remain the same, but more luminous flux is reaching the eye.

Basic to the entire study and use of color is the field of color specification. It can be seen from the foregoing that hue designations alone would give a very incomplete idea of color. Further, the large number of hues points up the necessity for some kind of system. But before methods of color specification can be discussed, three basic difficulties should be pointed out.

The first difficulty is that there is no one-to-one correspondence between the energy output of a source and the observer's perception of its brightness. As explained earlier, radiant energy at different wave lengths produces different sensations of brightness even though the amount of energy is the same at each wave length (Figs. 2.10 and 2.11).

The second difficulty is that human observers have trouble judging absolute levels of brightness, saturation, and hue. These are psychological judgments, difficult to make under ideal circumstances and [illegible]re difficult if certain other psychological events occur at the same time. For example, su[illegible] object of a certain hue and brightness is shown first by itself and then next to an object of [illegible] hue and brightness; the hue and brightness of the first object will appear to change, eve[illegible]gh the energy emitted from it remains the same physically.

The third difficulty is that the color of an object depends just as much on the spectral characteristics of the illuminant as it does on the nature of the object. As most people are aware, for example, fabrics change color when moved from the light of ordinary tungsten-filament bulbs to fluorescent light. Any accurate system of color specification must account for this fact by relating the color to a standard light source.

The Tristimulus Method of Color Specification

To date, the most objective and accurate method of specifying colors other than spectrum colors is the tristimulus method. It can be shown that any color can be matched by properly combining three pure spectrum colors called primary colors. If a colored sample is placed in one half of a photometric field, a mixture of three primary colors -- red, green, and blue, for example -- in the other half of the field can be made to match the colored sample. This is done by varying the relative brightness of the three primary colors. Such a procedure is called tristimulus colorimetry; the instrument used is a colorimeter.

A drawback to this method is that, as we have seen, the matching judgment of one observer cannot be taken as representative. Only when a large number of observers are used in each experiment can consistent values be obtained for the relative brightness of primary colors required to match any given color.

In order to avoid this difficulty and to make the procedure as objective as possible, the tristimulus method was revised and standardized by the International Commission on Illumination (ICI). Three primary colors were agreed upon. Then, by experiments with a number of normal observers, standard values for the relative amounts of each primary color were established to match each wave length in the visible spectrum. With these values available in tabular form, a more objective and economical technique may be used to specify color.

The first step is to determine the spectral composition of the color sample with a spectrophotometer. The results of such measurements are shown for a sample of green paint in Figure 2.13. The reflection factor at each wave length of the sample, or at small wave length intervals, is multiplied by each of the ICI tristimulus values for that wave length. The resulting values are summed over all wave lengths for each primary separately. The results are three values, X, Y, and Z, each of which represents the total contribution of one of the three primaries to the color of the sample.

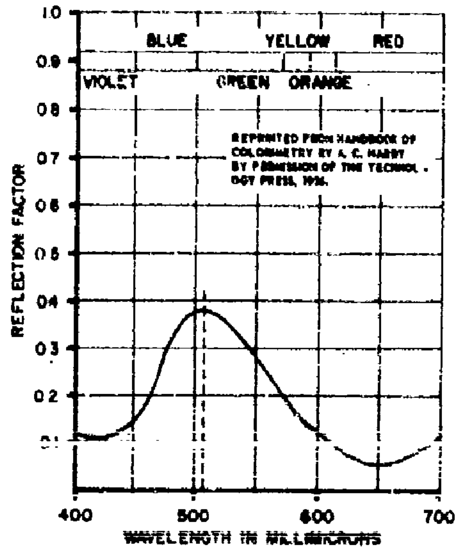


Figure 2.13 Spectral Reflection Curve of a Typical Green Paint

The sample reflects 38 percent of all the energy reaching it at 500 $m\mu$ but only 5 percent at 650 $m\mu$. (from Hardy2-3)

One more point is important here. It was pointed out earlier that the color of a sample depends not only on its own characteristics but also on the spectral emittance of the light source under which it is viewed. Therefore, for each spectrum color, not one but three sets of ICI tristimulus values have been determined, each for a different standard source of illuminance. Illuminant A represents the spectral emittance of most tungsten-filament incandescent lamps. Illuminant B represents the spectral emittance of average noon sunlight. Illuminant C represents the spectral emittance of average daylight. In specifying a color that is going to be used under known conditions of illumination, the tristimulus values for the standard illuminant conforming most closely to those conditions should be used. In addition, special sets of tristimulus values may be derived for illuminants whose spectral emissions differ greatly from those of the three standards.

The ICI tristimulus values can be plotted graphically with cartesian coordinates, if the following transformations are made:

$$x = \frac{X}{X + Y + Z} \qquad (1) \qquad\qquad y = \frac{Y}{X + Y + Z} \qquad (2)$$

where X, Y, and Z are the amounts of the three primaries in any sample and x and y are the "trichromatic coefficients" in the ICI system. The abscissa of the graph becomes x and the ordinate becomes y; z may be obtained from the relationship $x + y + z = 1$. Such a graph, shown in Figure 2.14, is called a chromaticity diagram.

Any color may be located on the diagram by specifying its trichromatic coefficients. The solid curved line is the locus of all the spectrum colors. Purple, not a spectrum color but a mixture of red and violet, has its locus in the straight line joining the ends of the visible spectrum (400 to 700 $m\mu$). In Figure 2.14, the color of one of the ICI standard illuminants, Illuminant C, has been plotted from its trichromatic coefficients. It is represented by point C. If desired, the trichromatic

coefficients of other illuminants (including the other two ICI standards) may be similarly located in the diagram. While Illuminant C is used most frequently, care must be taken to specify the illuminant under which a color is to be viewed, especially if its spectral emittance is unusual.

From the chromaticity diagram, a color can be specified in terms of dominant wave length, purity, and complementary wave length. The final component, brightness, can be obtained from the tristimulus values. As an illustration, take the sample of green paint whose spectral reflection factors were plotted in Figure 2.13; assume it is to be viewed under Illuminant C. By multiplying the reflection factors by each tristimulus value at each wave length and summing up for each primary, the tristimulus values of the sample are found to be X = 15.5, Y = 24.2, and Z = 22.64. By equations (1) and (2), the trichromatic coefficients of the sample are found to be x = 0.25 and y = 0.39. The color sample thus falls at point G on the chromaticity diagram, Figure 2.14. The color is specified as follows

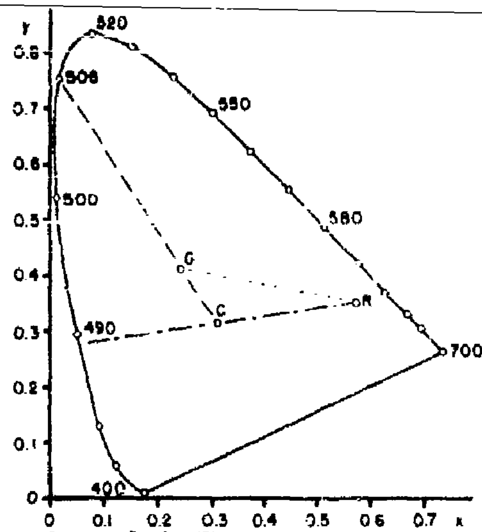


Figure 2.14 Chromaticity Diagram

G Represents the green paint in Figure 2.13; C is Standard Illuminant C, R is a red sample.

1. Dominant wave length. To find out generally what the sample looks like, draw a straight line (dashed) from the illuminant, C, through the sample, G, to the spectrum locus (solid line) on the chromaticity diagram. It intersects the locus at 506 mμ. This is the dominant wave length of the sample; it shows that the sample looks something like a blue-green. It also means that the sample can be exactly matched by adding the proper amount of Illuminant C to a pure spectrum color of 506 mμ.

Clearly, then, the concept of dominant wave length is a psychophysical, and more precise, equivalent of the concept of hue.

2. Purity. The chromaticity diagram shows that all combinations of Illuminant C and a spectrum color of 506 mμ must lie on the straight line joining them. The color G is merely one of the possible combinations. The less Illuminant C and the more 506 mμ (green) the sample contained, the nearer it would be to the spectrum locus; the purest green that could theoretically be obtained would fall right on the locus. The relative distance of the color along the line from C to the spectrum locus defines its purity. Thus, the green sample G has a purity of 20 percent. The spectrum colors have a purity of 100 percent, which, however, cannot actually be reproduced; the colors of the spectrum used in the ICI system are theoretical colors of unattainable purity.

It should be clear now that the concept of purity is the psychophysical equivalent of the concept of saturation.

3. Complementary wave length. If two colors, mixed together, appear achromatic (i.e., a gray having the same trichromatic coefficients as the illuminant), their dominant wave lengths are said to be complementary. To find the complementary wave length of a color sample on the chromaticity diagram, extend its dominant wave length line back through the illuminant point until it intersects the spectrum locus on the opposite side. The spectrum value at the intersection is the complementary wave length. It can be seen that the green sample G does not have a complementary wave length, because an extension of the line from G through C would not intersect the spectrum locus. However, the red sample indicated by R has a complementary wave length of 486 mμ.

Since purple is not a spectrum color, it has no dominant wave length. However, we can specify a given sample of purple by its complementary wave length, which is a spectrum color. In this case, a "c" is put after the wave length to show that it is complementary (e.g., 530 c).

4. Brightness. It has been shown that the sensation of brightness differs for different wave lengths when the amount of radiant energy is the same. For the primary Y in the ICI system, a green of 555 mμ was chosen whose distribution in the spectrum colors exactly paralleled that of the photopic

luminosity curve (Fig. 2.10). The relative brightness of a sample is therefore given by the ratio between the total amount of Y in the sample and the total amount of Y in a perfectly reflecting (or transmitting) sample viewed under the same illuminant. Suppose a sample of color has the tristimulus values X = 31.0, Y = 48.4, and Z = 45.3. It has the same trichromatic coefficients as the green sample shown in Figure 2.13 (x = 0.25; y = 0.39), and it will appear at the same point, G, on the chromaticity diagram. Because it possesses twice the amount of the Y primary, however (48.4 against 24.2), it is twice as bright as the green sample in Figure 2.13.

Other Methods of Color Specification

Color may also be specified by visually matching samples with printed, dyed, or painted standards. Such specification is frequently used in the paint and textile industries. One such system is the widely used Munsell system, named after its author. Like a number of these systems, the Munsell system is based on a color solid whose coordinates are like those in Figure 2.15, and it is fairly representative of color systems based on solids. The colors are arranged according to their psychological properties of hue, saturation, and brightness. (The Munsell system substitutes the word chroma for saturation and the word value for brightness.) The solid is most easily described in terms of a horizontal circle with a vertical axis. Hues are arranged radially around the circle. Saturation (chroma) increases from the vertical axis outward in a horizontal plane. Colors at the vertical axis are achromatic, while the completely saturated spectrum colors fall on the rim of the circle. Complementary colors are diametrically opposed. Brightness (value) is represented by the vertical axis. It runs from the extreme dark at the "south pole" to extreme light at the "north pole." The Munsell Atlas[2-7] contains painted samples of all the colors in the system, arranged either in vertical planes or horizontal planes through the solid.

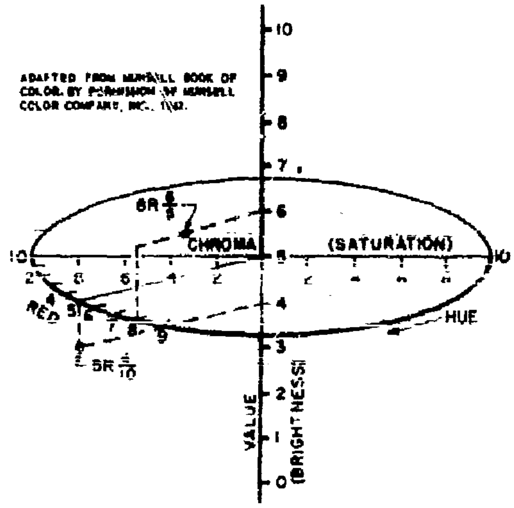


Figure 2.15 A Prototype Color Solid (after Munsell[2-5])

Colors in the Munsell system are completely specified by symbols that designate their hue, chroma, and value. For example, a certain vermillion is specified 5 R 4/10 (Fig. 2.15). The 5 R designates the fifth (or medium) red in the hue sequence, 4 designates its value, and 10 its chroma. Therefore 5 R 4/10 is a red without any tendency towards yellow or purple, its value is a little darker than a medium gray, and it is completely saturated (approximating the saturation of a spectrum color). Another red, 8 R 6/5 would contain a moderate amount of yellow, it would be lighter in value than the other red, and it would be less saturated (i.e., less chromatic). The purest yellow obtainable is 5 Y 8/9, which would be a yellow of high brightness (value) and saturation (chroma) falling high above the plane of the circle in Figure 2.15.

Color Mixing

The ICI, Munsell, and some other systems of color specification furnish information that can be used to mix colors with predictable results, though errors may be introduced by imperfect filters or pigments. There are two ways of mixing colors, additive and subtractive.

Additive color mixture occurs when several wave lengths of light are simultaneously reflected or transmitted into the eye from the same source. As stated earlier, the eye cannot separate the components. Therefore, the sensation of only a single color is aroused. This kind of mixing occurs in the process of colorimetry and forms the basis of the ICI system. Figure 2.16 gives an example of additive color mixing. If two samples are located on the chromaticity diagram, Figure 2.14, the straight line joining them represents the locus of all the possible mixtures of the two. For example,

the trichromatic coefficients of any mixture of the red, R, and the green, G, on the diagram will fall somewhere on the dotted line joining them. To find the trichromatic coefficients of any additive mixture, merely add the tristimulus values of the components and substitute the results for X, Y, and Z in equations (1) and (2), given earlier in this chapter.

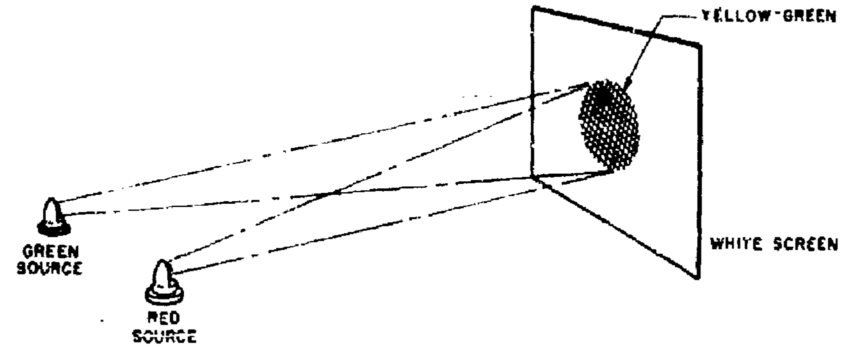
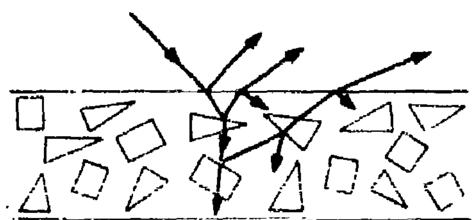


Figure 2.16 Additive Color Mixing by Means of Projected Light

Subtractive color mixture occurs when light travels through or is reflected by two or more filtering mediums, each of which absorbs certain wave lengths of the spectrum. The light that finally reaches the eye is that which has not been absorbed (subtracted) along the way. Figure 2.17 shows what happens when pigments are mixed so as to cause a subtractive mixture. The vehicle, the amount of dilution, the base, and many other variables enter into subtractive mixtures of paints and dyes. Results are therefore difficult to predict precisely. Experience with the particular media is important in subtractive mixtures.



REPRINTED FROM PRINCIPLES OF PHYSICS - III - OPTICS, BY F. W. SEARS BY PERMISSION OF ADDISON WESLEY PUBLISHING COMPANY, INC. 1949.

Figure 2.17 The Course of a Single Beam of Light Through a Mixture of Two Pigments (from Sears2-6)

LIST OF REFERENCES

2-1 Chapanis, A., "How We See: A Summary of Basic Principles." Chapter 1 in Human Factors in Undersea Warfare. National Research Council, Washington, D. C. 1949.

2-2 Gibson, K. S., and Tyndall, E. P. J., "Visibility of Radiant Energy." Scientific Papers of the Bureau of Standards. Vol. 19. 1923-1924.

2-3 Hardy, A. C., Handbook of Colorimetry. The Technology Press, Cambridge, Mass. 1936.

2-4 Hecht, S. and Williams, R. E., "The Visibility of Monochromatic Radiation and the Absorption Spectrum of Visual Purple." J. Gen. Physiol. Vol. 5. 1922. pp. 1-33.

2-5 Munsell, A. H., Munsell Book of Color. Munsell Color Company, Inc., Baltimore, Md.

2-6 Sears, F. W., Principles of Physics. III. Optics. Addison-Wesley Press, Reading, Mass. 1948.

GENERAL BIBLIOGRAPHY

2-7 Anon. Determination of Fundamental Colors from Chromatic Adaptation Data. Contract No. Nonr-1066(00). Project NR140-061. Office of Naval Research. 1954. Prepared by Ohio State University.

2-8 Anon. A Guide to the Color Systems. Kroch's Bookstores, Inc., Chicago, Ill.

2-9 Anon. "I. E. S. General Guide to Photometry." Illum. Engng. Vol. 50 March-April 1955.

2-10 Anon. Illuminating Engineering Nomenclature and Photometric Standards. American Standard Z7.1. 1942.

2-11 Anon. Interconversion Tables for Photometric Units. A.R.L./N. 1/0.288. Admiralty Research Laboratory, Teddington, Middlesex, England. October 27, 1944.

2-12 Anon. Proceedings of the Eighth Session. International Commission on Illumination, Cambridge, Mass. 1931. pp. 19-29.

2-13 Anon. The Science of Color. Committee on Colorimetry, Optical Society of America. Thomas Y. Crowell Company, New York, N. Y. 1953.

2-14 Anon. "Specification and Description of Color." American Society for Testing Materials Bull. No. 119, 1942. pp. 19-20.

2-15 Anon. Standards to be Employed in Research on Visual Displays. Armed Forces - NRC Vision Committee. October 1947. revised March 1950.

2-16 Anon. Symposium on Color. Inter-Society Color Council. Arranged in Cooperation with the Society of Motion Picture Engineers. February 1949.

2-17 Anon. Symposium on Color Difference Specification. Presented at Meeting of Committee E-12 on Appearance, American Society for Testing Materials, Cleveland, Ohio. March 5-6, 1952.

2-18 Anon. Tables for Transforming Chromaticity Coordinates from the I.C.I. System to the R-U-C-S System. Letter Circular LC897. Photometry and Colorimetry Section, National Bureau of Standards. May 1948.

2-19 Bartley, S. Howard, Brightness Enhancement in Relation to Target Intensity. 1951.

2-20 Bartley, S. Howard, and Seibel, Jean L., "A Further Study of Entoptic Stray Light" J. Psychol. Vol. 38. 1954. pp. 313-319.

2-21 Bartley, S. Howard, and Wilkinson, Frank, "Brightness Enhancement When Entoptic Stray Light is Held Constant." J. Psychol. Vol. 33. 1952.

2-22 Bartley, S. Howard, and Wilkinson, Frank, "Certain Factors in Producing Complexity of Response to a Single Pulse of Light." J. Psychol. Vol. 35. 1953.

2-23 Blackwell, H. Richard, "Evaluation of the Neural Quantum Theory in Vision." Amer. J. Psychol. Vol. 66. July 1953. pp. 397-408.

2-24 Bouman, M. A., "Absolute Threshold Conditions for Visual Perception." J. Opt. Soc. Amer. Vol. 45. January 1955. pp. 36-43.

2-25 Bouman, M. A., "Quanta Explanation of Vision." Documenta Ophthalmologica: Advances in Ophthalmology. Vol. 4. 1950, pp. 23-115.

2-26 Bouman, M. A., and Van Der Velden, H. A., "The Quanta Explanation of Vision and Brightness Impression for Various Times of Observation and Visual Angles." J. Opt. Soc. Amer. Vol. 38. March 1948. pp. 231-236.

2-27 Boynton, Robert M., Stray Light in the Eye.

2-28 Breckenridge, F. C., and Schaub, W. R., "Rectangular Uniform-Chromaticity-Scale Coordinates." J. Opt. Soc. Amer. Vol. 29. September 1939. pp. 370-380.

2-29 Brennan, Josephine G., Burnham, R. W., and Newhall, S. M., "Color Terms and Definitions." Psychol. Bull. Vol. 45. 1948. pp. 207-230.

2-30 Brindley, G. S., "The Bunson-Roscoe Law for the Human Eye at Very Short Durations." J. Physiol. Vol. 118. 1952. pp. 135-139.

2-31 Brown, R. H. and Niven, Jorma I., "The Relation Between the Foveal Intensity Threshold and Length of an Illuminated Slit." J. Exp. Psychol. Vol. 34. 1944. pp. 464-476.

2-32 Burnham, Robert W., "A Colorimeter for Research in Color Perception." Amer. J. Psychol. Vol. 65. October 1952. pp. 603-608.

2-33 Chapanis, A., Photometric Units. U. S. Army Air Forces, Materiel Center, Experimental Engineering Section. November 19, 1942.

2-34 Chapanis, A. and Halsey, Rita M., "Luminance of Equally Bright Colors." J. Opt. Soc. Amer. Vol. 45. January 1945. pp. 1-6.

2-35 Cheskin, Louis, Notation on a Color System: For Color Planning, Color Identification, Color Mixing-Matching, Printing With Color. Color Research Institute of America. 1949.

2-36 Cohen, Jozef, "Multichromatic Colorimeters." Illum. Engng. Vol. 49. No. 1. January 1954. pp. 50-58.

2-37 Davidson, Hugh R., and Hanlon, J. J., "Use of Charts for Rapid Calculation of Color Difference." J. Opt. Soc. Amer. Vol. 45. No. 8. August 1955.

2-38 Denton, E. J., and Pirenne, M. H., "The Absolute Sensitivity and Functional Stability of the Human Eye." J. Physiol. Vol. 123. No. 3. 1954. pp. 417-442.

2-39 Denton, E. J., and Pirenne, M. H., "The Minimum Number of Quanta Necessary for Vision." Proc. Physiol. Soc. September 28-29, 1951 (abstract); original article in J. Physiol. Vol. 115. 1951.

2-40 De Vries, Hl., "Light Quanta and Vision." Revue D'Optique. Vol. 28. No. 2. 1949. pp 101-104.

2-41 De Vries, Hl., "The Quantum Character of Light and its Bearing Upon Threshold of Vision, The Differential Sensitivity and Visual Acuity of the Eye." Physica. Vol. 10. July 1943. pp. 553-564.

2-42 Evans, R. M., An Introduction to Color. John Wiley and Sons, New York, N. Y. 1948.

2-43 Gibson, G. L., and Neubrech, D. A., "Automatic Photoelectric Colorimeter for Direct Reading of Munsell Coordinates." J. Opt. Soc. Amer. Vol. 44. September 1954. pp. 703-712.

2-44 Gibson, K. S., "Spectrophotometry." National Bureau of Standards Circular 484. Issued September 1949

2-45 Graham, C. H., and Bartlett, N. R., "The Relation of Size of Stimulus and Intensity in the Human Eye: II. Intensity Thresholds for Red and Violet Light." J. Exp. Psychol. Vol. 24. 1939. pp. 574-587.

2-46 Graham, C. H., Brown, R. H., and Mote, F. A., "The Relation of Size of Stimulus and Intensity in the Human Eye: I. Intensity Thresholds for White Light." J. Exp. Psychol. Vol. 24. 1939. pp. 555-573.

2-47 Guilford, J. P., Psychometric Methods, Second Edition. McGraw-Hill Book Company, New York, N. Y. 1954.

2-48 Halsey, Rita M., "A Comparison of Three Methods for Color Scaling." J. Opt. Soc. Amer. Vol. 44. 1954. pp. 199-206.

2-49 Hanes, R. M., "The Construction of Subjective Brightness Scales from Fractionation Data: A Validation." J. Exp. Psychol. Vol. 39. October 1949. pp. 719-728.

2-50 Hanes, R. M., "A Scale of Subjective Brightness." J. Exp. Psychol. Vol. 39. August 1949. pp. 438-452.

2-51 Hardy, A. C. and Perrin, F. H., The Principles of Optics. McGraw-Hill Book Company, New York, N. Y. 1932.

2-52 Harrison, T. H., Subcommittee C (Luminescent Materials) Report RC(C)9. Ministry of Home Security, Civil Defense Research Committee. April 4, 1940. (CONFIDENTIAL)

2-53 Hochberg, J. E., Triebel, W., and Seaman, G., "Color Adaptation Under Conditions of Homogeneous Visual Stimulation." J. Exp. Psychol. Vol. 41 1951. pp. 153-159.

2-54 Hecht, Selig, "Energy and Vision." Amer. Scientist. Vol. 32. July 1944. pp. 159-177.

2-55 Hecht, Selig, Shlaer, Simon, and Pirenne, Maurice H. "Energy at the Threshold of Vision." Science. Vol. 93. 1941. pp. 585-587.

2-56 Holway, A. H., "On the Precision of Photometric Observations." J. Opt. Soc. Amer. Vol. 27. 1937. pp. 120-123.

GENERAL BIBLIOGRAPHY (Cont)

2-57 Jameson, Dorothea, and Hurvich, Leo M., "Use of Spectral Hue-Invariant Loci for the Specification of White Stimuli." J. Exp. Psychol. Vol. 41. June 1951. pp. 455-463.

2-58 Judd, D. B., "Basic Correlates of the Visual Stimulus." In: S. S. Stevens (Ed.), Handbook of Experimental Psychology. John Wiley and Sons, New York, N. Y. 1951. pp. 811-867.

2-59 Judd, D. B., "Estimation of Chromaticity Differences and Nearest Color Temperature on the Standard 1931 ICI Colormetric Coordinate System." J. Opt. Soc. Amer. Vol. 26. November 1936. pp. 421-426.

2-60 DeLange Dzn, H., "Relationship between Critical Flicker-Frequency and a Set of Low Frequency Characteristics of the Eye." J. Opt. Soc. Amer. Vol. 44. 1954. pp. 380-389.

2-61 Lee, Richard H., Finch, E. M., and Ponds, G. A., "Periodic Fluctuations in the Dark Adapted Threshold." Amer. J. Physiol. Vol. 143. 1945. pp. 6-10.

2-62 Leibowitz, Herschel., "Photometric Scales and the Duplicity Theory of Vision." Amer. J. Psychol. Vol. 65. October 1952. pp. 632-634.

2-63 Lerner, Henry H., "Biophotometric Measurements of Dark Adaptation." Amer. J. Roentgenol. & Radium Therapy. Vol. 45. 1941. pp. 753-755

2-64 MacAdam, D. L., "Dependency of Color-Mixture Functions on Choice of Primaries." J. Opt. Soc. Amer. Vol. 43. 1953. pp. 533-538.

2-65 MacAdam, D. L., "The Fundamentals of Color Measurement." J. Soc. Motion Picture Engineers Vol. 31. 1938. pp. 343-348.

2-66 MacAdam, David L., "Specification of Small Chromaticity Differences." J. Opt. Soc. Amer. Vol. 33. 1943. pp. 18-26.

2-67 MacAdam, D. L., "Truncated Weighted Ordinate Integrations in Colorimetry." J. Opt. Soc. Amer. Vol. 43. July 1953. pp. 622-623.

2-68 Middleton, W. E. Knowles, "Comparison of Colorimetric Results from a Normal-Diffuse Spectrophotometer with Those from a 45-Degree-Normal Colorimeter for Semiglossy Specimens." J. Opt Soc. Amer. Vol. 43. December 1953. pp. 1141-1143.

2-69 Middleton, W. E. Knowles., "A Registering Low-Level Photometer." J. Opt Soc. Amer. Vol. 44. April 1954. pp. 303-305.

2-70 Moreland, J. D., "Modifications of the Wright Trichromatic Colorimeter for Extrafoveal and Peripheral Observations." Optica Acta. Vol. 2. July 1955. pp. 101-104.

2-71 Mueller, Conrad G., "Frequency of Seeing Functions for Intensity Discrimination at Various Levels of Adapting Intensity." J. Gen. Physiol. Vol. 34. March 1951. pp. 463-474.

2-72 Mueller, Conrad G., "Quantum Concepts in Visual Intensity-Discrimination." Amer. J. Psychol. Vol. 63. January 1950. pp. 92-100.

2-73 Munsell, A. H., Munsell Book of Color (Defining, Explaining and Illustrating the Fundamental Characteristics of Color). Revision and Extension of the "Atlas of the Munsell Color System," Munsell Color Company, Baltimore, Md.

2-74 Neugebauer, H. E. J., "Standardization in Colorimetry." Z. Wiss Phot. Vol. 44. No. 10-12. 1949. pp. 193-203. Translated from German by Carlo A. Bauman. Translation No. T-1943.

2-75 Newhall, Sidney M., "The Constancy of the Blue Arc Phenomenon." J. Opt. Soc. Amer. Vol. 27. April 1937. pp. 165-176.

2-76 Newhall, Sidney M., "An Instrument for Color Stimulation and Measurement." Dodge Commemorative Number, Psychol. Monographs. Vol. 47. No. 212. 1936. pp. 199-216.

2-77 Newhall, Sidney M. and Brennan, Josephine G., Comparative List of Color Terms. Inter-Society Color Council, Washington, D. C. January 1949.

2-78 Nickerson, Dorothy, "The Illuminant in Textile Color Matching." J. Opt. Soc. Amer. Vol. 38. 1948. pp. 458-466.

2-79 Pirenne, M. H., "The Absolute Sensitivity of the Eye and the Variation of Visual Acuity with Intensity." Brit. Med. Bull. Vol. 9. No. 1. 1953. pp. 61-67.

2-80 Pirenne, M. H., and Denton, E. J., "Quanta and Visual Thresholds." J. Opt. Soc. Amer. Vol. 41. June 1951. pp. 426-427.

2-81 Pirenne, M. H., and Marriott, F. H. C., "Quantum Theories of the Absolute Threshold: The Influence of Retinal Position and Area." Optica Acta. Vol. 1. No. 3. December 1954. pp. [illegible].

2-82 Pritchard, B. S., Design and Construction of Photoelectric Photometers for Field and Laboratory Use. Project 2144-329-M, Research Report 20. Optics and Vision Group, University of Michigan Vision Research Laboratories. July 2, 1955.

2-83 Reimann, G., Judd, D. B., and Keegan, H. J., "Spectro-Photometric and Colorimetric Determination of the Colors of the TCCA Standard Color Cards." Research Paper RP 1700. Journal of Research National Bureau of Standards. Vol. 36. March 1946. pp. 209-247.

2-84 Rhael, Edward W., Color and Instrumentation. Sandoz Chemical Works, Inc., U. S. 146, New York, N. Y.

2-85 Richter, Manfred, "The Fundamental Law of Colorimetry." Z. Wiss. Phot. Vol. 43. April 1949. pp. 246-251. Translated from German by M. W. Seymour. Translation No. T-1710.

2-86 Richter, Manfred. "The Official German Standard Color Chart." J. Opt Soc. Amer. Vol. 45. March 1955. pp. 223-226.

2-87 Sanders, C. L., Stevens, B. A., and Middleton, W. E. Knowles, "The Primary Standard of Luminous Intensity at the National Research Council of Canada." J. Opt. Soc. Amer. Vol. 44. January 1954. pp. 88-89.

2-88 von Schelling, Hermann, Correction Factor to the Photometric Square Law for Area of Source and Receiver. Medical Research Laboratory, U. S. Naval Submarine Base, New London, Conn. No. 16. Report No. 231. July 27, 1953. NM 003 041.40.03.

2-89 von Schelling, Hermann, Three Charts for Measuring Chromaticity Shifts Resulting from Changes in Illumination, Macular Pigmentation, and Intraocular Absorption. Medical Research Laboratory, U. S. Naval Submarine Base, New London, Conn. No. 27. Report No. 210. Oct. 14, 1952. BuMed. & Surg. NM 003 041.19.03.

2-90 Simpson, G. C., The Photometric Conversion Diagram. Great Britain, Ministry of Home Security, Civil Defense Research Committee, Subcommittee G (Photometric Properties of the Atmosphere) Report RC (G) 15. March 21, 1942. OSRD No. WA-162-33.

2-91 Stearns, E. I., "Whats New in Spectrophotometry: Progress of Spectrophotometry in the Textile Industry." Calco Tech. Bull. No. 820. April 13, 1951. (American Cyanamid Company).

GENERAL BIBLIOGRAPHY (Cont)

2-92 Stevens, S. S., "Decibels of Light and Sound," Physics Today. Vol. 8. No. 10. October 1955. pp. 12-17.

2-93 Sturrock, Walter, and Staley, Karl A., Light: Its Measurement and Control. LS-154. General Electric, Application Engineering Dept. September 1953.

2-94 Sweet, Monroe H., "An Improved Photomultiplier Tube Color Densitometer," J. Soc. Motion Picture Engineers. Vol. 54. January 1950.

2-95 Walsh, J. W. T., Photometry, Second-Edition. Constable and Company, Limited. 1953.

2-96 Weaver, K. S., "A Provisional Standard Observer for Low Level Photometry," J. Opt. Soc. Amer. Vol. 39. 1949. p. 278.

2-97 Wertheimer, M., "The Variability of Auditory and Visual Absolute Thresholds in Time," J. Gen. Psychol. Vol. 52. 1955. pp. 111-147.

2-98 White, C. T., Design of a Color-Matching Dosimeter. PO 53401, NE 121303-3 NEL3B2I. U. S. Navy Electronics Laboratory, San Diego, Calif. November 23, 1953.

2-99 Wolf, Ernst, "Effects Ultraviolet Radiation on Visual Thresholds." Science. Vol. 105. April 1947. pp. 105-366.

2-100 Wright, W. D., Photometry and the Eye. Hatton Press Limited, London, England. 1949.

2-101 Wyszecki, Gunter, "A Graphical Interpretation of a Three-Components Theory of Chromatic Adaptation in Terms of the CIE Chromaticity Diagram." J. Opt. Soc. Amer. Vol. 44. 1954. pp. 787-792.

2-102 Young, Francis A., and Biersdorf, William R., "Pupillary Contraction and Dilation in Light and Darkness." J. Compar. Physiol. Psychol. Vol. 47. 1954. pp. 264-268.

2-103 Zoethout, W. D., Physiological Optics. The Professional Press, Inc., Chicago, Ill. 1947.

CHAPTER 3

ANATOMY OF THE EYE

This chapter describes the eye and how it functions. The word "eye" in this chapter means the opaque white sphere, commonly called the eyeball, with its transparent corneal bulge and internal components. Muscles attached to this sphere position it in its bony cavity and turn it as a unit; that is, "eye movement" is turning of the eyeball about either a vertical or horizontal axis. For descriptive purposes, these muscles, as well as the fat that cushions the eye, the eyelids, tear glands, and other structures outside the sphere are considered "surrounding structures" rather than part of the eye.

In dealing with visual performance, the parts of the eye which are directly related to image formation, image quality, and perception seem more important than the others, and these are emphasized here. They include the cornea, which acts as the first lens in the optical system; the crystalline lens in the interior of the eye, whose curvature can be changed for focusing of near or distant objects; the iris, which can constrict the pupil over the lens or dilate the pupil for a rough adjustment to the amount of light entering the eye; and the retina, the eyeball's thin interior lining, which contains millions of photosensitive receptors, called the cones and rods. Most of the cones are concentrated in a small central spot on the retina called the fovea, which distinguishes color and detail. The rods, though unable to pick up detail, are chemically and structurally equipped to respond to much lower illumination than the cones. They are used for night vision. Single fibers from each foveal cone, from each group of rods, and from groups of cones outside the fovea go all the way to the brain via the optic nerve, which is actually a "bundle" of nerve fibers: the lateral geniculate body, which is a relay station; and the optic radiations, which spread out to the visual cortex of the brain. The optic nerve leaves the retina about 15° toward the nose from the fovea.

THE STRUCTURE OF THE EYE

Structures Around the Eye

The human eyes lie protected in a pair of irregular, somewhat conical, bony cavities in the skull called the orbits. Each eye is cushioned in its bony cup by masses of fat. It is supported by ligaments, fat, and the six extraocular muscles that turn the eye (Fig. 3.1). The eyes can be turned approximately 50 degrees to either side of the resting position, 40 degrees above, and 60 degrees below. They can also be moved in torsion about the optical axis, though this motion is limited to less than 10 degrees.

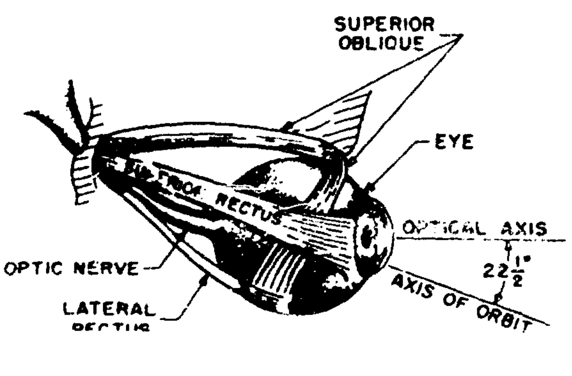


Figure 3.1 The Eye Positioned in the Orbit

The open end of the orbit is curtained by the eyelids, folds of skin that move together to cover the eye or pull apart to expose it. The lids play an important role in keeping the eyeball clean and moist, for if the eyeball becomes dry, vision is impaired. Involuntarily, every two to ten seconds the lids sweep moisture across the front of the eyeball (blinking). Involuntarily, blinking also occurs to protect the eye from too-bright light, from dirt particles on the eye, and from objects that move rapidly toward the eye. In some cases, involuntary blinking can be avoided or postponed. Voluntary blinking is also possible. Since even a normal blink (for moistening, with no threat present) lasts 0.3 to 0.4 second, blinking may involve a critical loss of vision when a man is moving at hundreds of feet per second.

Components of the Eye

From the outside, the eye looks like an opaque white sphere with a transparent bulge, the cornea, at the front (Fig. 3.2). The eye is about 24 mm in diameter. The corneal bulge has a horizontal radius of about eight mm and a vertical radius of about six mm, and occupies about one-sixth of the surface area.

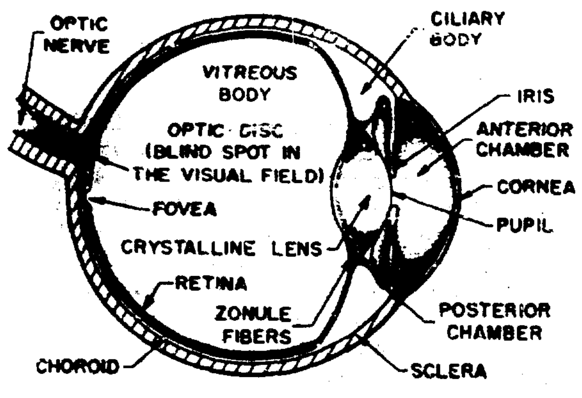


Figure 3.2 Cross Section of the Right Eye from Above

The white surface is a tough envelope called the sclera that protects and supports the components of the eye inside it. The back of the sclera is pierced by a number of blood vessels and nerves entering or leaving the eye. The most important of these nerves is the optic nerve. This nerve, throughout its extent approximately 1.5 to 3 mm in diameter, passes into the skull through the opening at the apex of the orbit. It transmits all visual stimulation from the eye to the brain.

The cornea is the window through which light enters the eye. Optically speaking, it is the first lens in the optical path of the eye.

Immediately inside the sclera is a thin, dark brown lining of blood vessels, the choroid. These vessels furnish nutrition for the eye (Fig. 3.2). The choroid reduces the amount of light entering through the walls and also reduces internal reflections. Toward the front of the eye, near the junction of the sclera and the cornea, the choroid layer thickens to form the muscular ciliary body. The front portion of the ciliary body leaves the wall of the eye, extending inward to form the iris.

The iris controls the amount of light entering the eye. It is a delicate membrane stretching across the interior of the eye at the base of the corneal bulge, with a circular opening (the pupil) near the center. The pupil can be dilated to admit more light to the eye or contracted to admit less. The pupil normally varies in diameter from approximately 2 to 8 mm, a ratio of pupillary areas of 1 to 16. On the other hand, it will be seen that the ratio of the weakest light the eye can see to the strongest it will tolerate is on the order of 1 to 10 billion, a striking example of nonlinearity of the eye's response.

Between the iris and the cornea is a space (the interior of the bulge) called the anterior chamber. It is filled with a clear liquid, the aqueous humor. The aqueous humor has a refractive index nearly the same as the cornea's, and so light rays do not bend significantly as they leave the cornea.

The crystalline lens lies immediately behind the iris, touching it near the pupil's edge. It provides adjustable focusing and absorbs and disperses harmful ultraviolet rays. The lens is constructed in several layers, but essentially it consists of a transparent, slightly yellow material contained in a very thin, springy capsule. The lens is convex on both surfaces. At its widest portion, at its center, it is about 3.7 mm thick. It is attached to the back portion of the ciliary body by a "guy-wire" system of tendons called the zonule fibers. When the ciliary muscle is contracted, the zonule fibers slacken, permitting the forward surface of the lens to bulge slightly. In this way they change the focus of the eye for near objects. Between portions of the iris and the zonule fibers is a small annular space, the posterior chamber, also filled with aqueous humor.

Back of the surface formed by the ciliary body, the zonule fibers, and the lens is another chamber of the eye. This is filled with a transparent, semi-solid gel, the vitreous body or vitreous humor. The vitreous body gives shape and substance to the eyeball, reduces refraction of light leaving the lens, and absorbs heat.

The wall of the vitreous chamber, from the ciliary body back, has a delicate, paper-thin, transparent lining called the retina. For all its thinness, the retina is a complex structure containing

receptors, nerve cells and fibers, blood vessels, and connective tissues. The physiology of the retina is described in some detail in the next paragraphs, because it explains some of the most important and unusual aspects of visual performance.

Components and Functions of the Retina

The retina is a light-sensitive layer that receives radiant energy and changes it into nerve impulses. These impulses are transmitted to the brain to give the sensation of light. The transformation of energies in the retina takes place within the photosensitive elements, which receive the light stimuli and initiate the impulses to the brain by way of the optic nerve. The various retinal elements and neural fibers have specialized functions and form a highly complex system.

The retina as a whole is made up of a layer of photosensitive receptors, two primary layers of neural connections, and subsequent neural-fiber pathways from the retina. Actually, ten layers of the retina can be distinguished, with fibers travelling in many directions within them. These layers are arranged so that light must first pass through the layers of fibers and connections before reaching the receptors. The receptors and their neural transmitters are divided into two working systems, the cone system and the rod system. The two systems differ in structural relationships, in distribution through the retina, and most important, in function. Their major functional difference is this: When the level of illumination is high, the cone system is functioning and we see both color and detail (photopic vision). When the illumination is lowered to a night-time level, the cone system can no longer function, and the rod system takes over. We now see everything as colorless -- in shades of gray -- with little or no detail (scotopic vision).

Cone System

Cone receptors are rather evenly distributed over most of the retina, but there are buildups in two areas: the central area, or fovea, and the extreme edge (see Fig. 3.3). By far the greatest

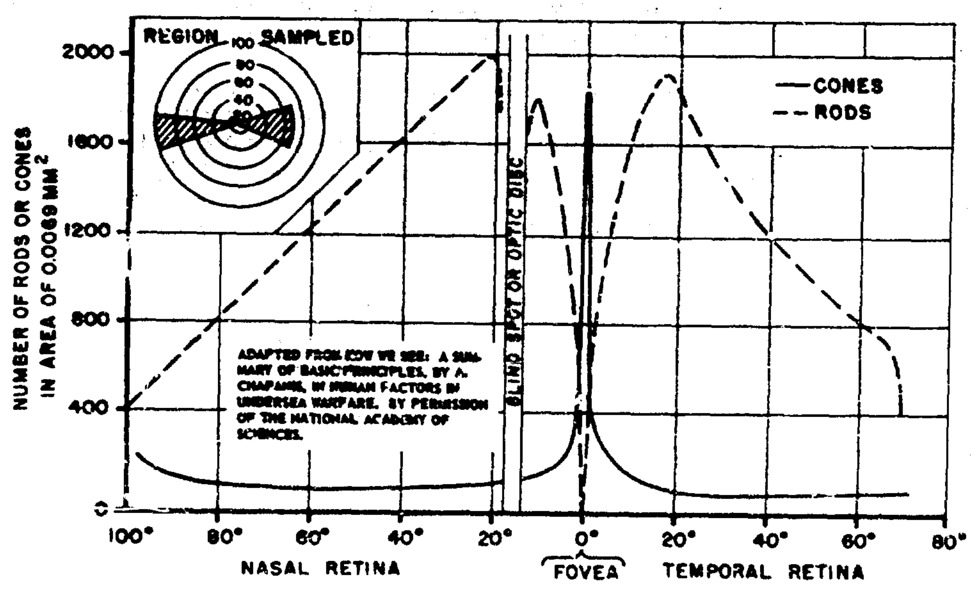


Figure 3.3 Density of Rods and Cones From Nasal to Temporal Edge of Retina (from Chapanis[3-1])

concentration is in the fovea; at its center, the fovea centralis, the density has been measured at 147,000 cones per square mm. The fovea is thus the area of acute vision. Its entire area is approximately 1.50 mm in diameter and subtends about 5 degrees of visual angle.* Near the ora serrata or the rim of the retina, the density of cones is about 16,300 per square mm, but this area is little used in vision. Like one-party telephones, the cone receptors in the fovea are connected

* 1 mm = 3.4° of visual angle

individually to the brain. The system is shown schematically in Figure 3.4. The foveal cone receptor is joined to two single nerve cells, one bipolar and one ganglion cell, connected in "series." These cells serve as transmitters. A fiber from the second cell extends to the brain by way of the optic nerve, which, as we shall see, is made up of individual nerve fibers. The cones outside the fovea, however, do not have individual connections. Instead, several receptors (cones, rods, or both) are linked together by branches from single neural pathways. In addition, various groups of receptor units may be linked together by horizontal cells and possibly by amacrine cells.

The cones respond to a wide range of light intensities. They can also adapt or adjust their sensitivity to suit relatively high prevailing levels of illumination above roughly .003 mL. These functions are accomplished by means of chemical changes in the photosensitive substance iodopsin, which they contain. Iodopsin breaks down under stimulation and regenerates when the stimulus is removed and to a lesser extent if the stimulus remains unchanged -- extremely complicated chemical processes that are still being studied.

ADAPTED FROM THE RETINA, BY S. L. POLYAK, 1941. BY PERMISSION OF THE UNIVERSITY OF CHICAGO PRESS.

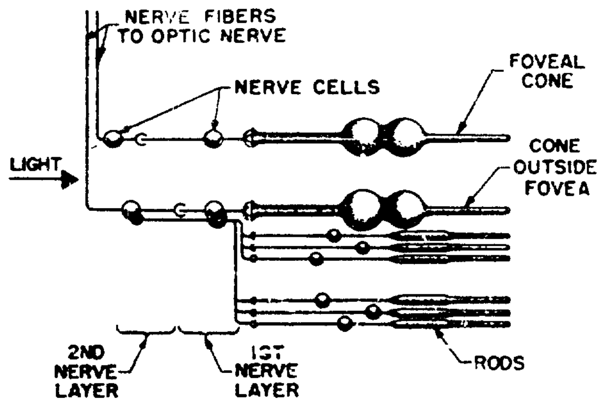


Figure 3.4 Schematic Diagram of the Rods and Cones and Their Underlying Neural Connections (after Polyak[3-3])

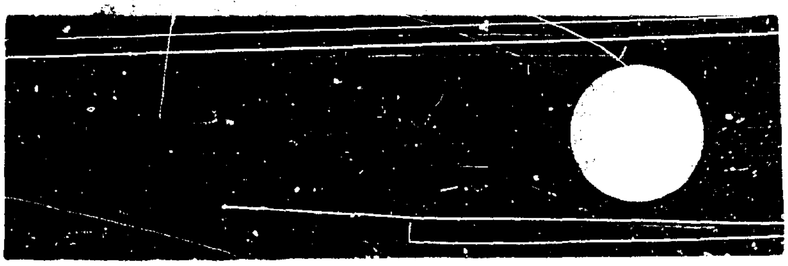
Rod System

The other retinal system is composed of the rod receptors and their underlying neural links. The rods are much less evenly distributed in the receptor layer of the retina than the cones (Fig. 3.3). They are completely absent from a very small central area that subtends about one degree of visual angle. Outside this area, they build up rapidly, reaching their maximum density of 150,000 to 170,000 per square mm at a distance of about 6 mm, or 18 to 20 degrees, from the fovea. From this point out to the extreme periphery, the density of rods gradually decreases to 30,000 to 50,000 per square mm. The neural connecting system for the rod receptors is much less specialized than for the foveal cones. No rod has individual links to the optic nerve pathway. Instead, several rods are joined to a single nerve cell, as shown in Figure 3.4. This nerve cell is joined to another nerve cell that sends a fiber to the brain by way of the optic nerve.

Rod receptors respond to lower light intensities than cones, for two reasons: (1) They contain rhodopsin (visual purple), a highly photosensitive material -- that is, it starts to break down when exposed to very low illumination; (2) Impulses from several rods are combined in a single neural pathway, as shown in Figure 3.4. The photochemical reaction is important. However, unless illumination is kept low, the breakdown of rhodopsin lowers its effective concentration, and the rods lose their sensitivity to low illumination; moreover, they do not recover it for some time after the illumination is cut off. Complete dark adaptation, the period for the rods to recover their full sensitivity, usually requires about 35 minutes. Very weak light impulses impinging on the individual rods are added up when they strike their common neural connection, and so produce a sensation. The sensitivity of the rod system varies over the retina. The rods are most sensitive where they are also most dense, about 18 to 20 degrees from the fovea.

Optic Disc

There is one place in the eye where the retina contains few if any receptors. It is where the nerve fibers from the retina are combined into the optic nerve and leave the globe. This absence of receptors produces a functional "blind spot." The optic disc, or blind spot, is located about 15 degrees from the fovea on the nasal side of the retina (Fig. 3.2 and Fig. 3.3). It covers an area about 7 degrees high and 5 degrees wide. In most circumstances we are unaware of its existence, because even when focusing on a point with one eye shut, we mentally fill in the gap left by the blind spot and, with both eyes open, the blind area of one eye is filled in by the other eye. However, the existence of the blind spot can be shown by means of Figure 3.5. With the left eye closed and the figure at eye level about 10 inches away, focus on the cross; the circle should disappear.

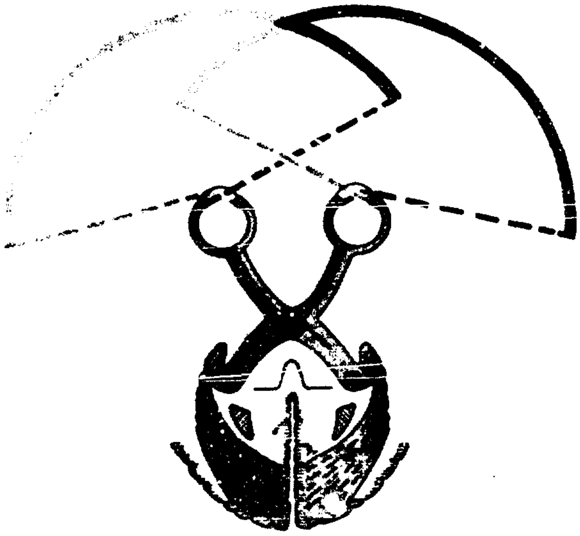


REPRINTED FROM TEXTBOOK OF OPHTHALMOLOGY BY W. S. DUKE-ELDER,
BY PERMISSION OF HIRSCHFELD BROTHERS LIMITED, 1934.

Figure 3.5 Blind Spot Test (from Duke-Elder[3-2])

OPTIC NERVES

The optic nerves from the two eyes extend backward and intersect at the chiasma (Fig. 3.6). Here, the nerve divides. Those fibers from the right half of both eyes form an optic tract that passes to the right side of the visual cortex of the brain. Those from the left half of both eyes form a second optic tract that passes to the left half of the cortex. From retina to geniculate body to visual cortex in the brain, each neural fiber maintains its individuality. Therefore, there is a point-to-point correspondence between the retina and the visual cortex of the brain, and the pattern of nervous impulses established in the retina is preserved in the cortex -- one impulse per foveal cone receptor, and a combined impulse for groups of rods and cones outside the fovea.



ADAPTED FROM TRAQUAIR'S CLINICAL PERIMETRY, 1957,
BY PERMISSION OF HIRSCHFELD BROTHERS, LIMITED

Figure 3.6 Visual Nerve Paths

The left sides of the retinas of both eyes are connected to the left side of the brain, and the right sides to the right side of the brain. (after Duke-Elder[3-2])

LIST OF REFERENCES

3-1 Chapanis, A., "How We See: A Summary of Basic Principles." Chapter 1 in Human Factors in Undersea Warfare. National Research Council. Washington, D. C. 1949.

3-2 Duke-Elder, W. S., Text-Book of Ophthalmology. The C. V. Mosby Co., St. Louis, Mo. 1934.

3-3 Polyak, S. L., The Retina. University of Chicago Press. 1941.

GENERAL BIBLIOGRAPHY

3-4 Anon. A Statistical Survey of the Variation of Pupil Diameters with High Field Brightness. OSRD No. WA-448. A.R.L./N.3/0.602, Admiralty Research Laboratory, Teddington, Middlesex, England. December 4, 1942.

3-5 Anon. Utilization by Humans of Carotenoid Pigments. F.I.A.T. Evaluation Report 1095. Field Information Agency, Tech. U. S. Office of Military Government for Germany, Office of the Director of Intelligence. August 21, 1945.

3-6 Alexander, L. T., and Bricker, P. D., Figure-ground Contrast and Binocular Rivalry. Contract N5-ori-166, T.O.I, Report 166-I-158. ONR, Naval Research Lab., Systems Coordination Div., Johns Hopkins University.

3-7 Allen, Frank, The Delineation of Retinal Zones with Dark Tube Vision. 1945.

3-8 Auerbach, E., and Wald, G., Identification of a Violet Receptor in Human Color Vision. 1954.

3-9 Auerbach, Edgar and Wald, George, "The Participation of Different Types of Cones in Human Light and Dark Adaptation." Amer. J. Ophthal. Vol. 39. February 1955.

3-10 Bartley, S. Howard, Brightness Comparisons when One Eye is Stimulated Intermittently and the Other Eye Steadily. 1952.

3-11 Bartley, S. H., "A Central Mechanism in Brightness Discrimination." Proc. Soc. for Exp. Biol. & Med. Vol. 33. 1958. pp. 535-536.

3-12 Bartley, S. Howard, Intermittent Photic Stimulation at Marginal Intensity Levels. 1951.

3-13 Bouman, M. A., "Mechanisms in Peripheral Dark Adaption." J. Opt. Soc. Amer. Vol. 42. December 1952. pp. 941-950.

3-14 Bouman, M. A., Peripheral Contrast Thresholds for Stimulating of Rod and Cone System by Background and Test Object Separately. Research Unit for Observations of the National Defense Research Council of the Netherlands, Kampweg 3, Soesterberg. February 1952.

3-15 Bouman, M. A., and Van Den Brink, G., "On the Integrate Capacity in Time and Space of the Human Peripheral Retina." J. Opt. Soc. Amer. Vol. 42. 1952. pp. 617-620.

3-16 Bouman, M. A., and Van Der Velden, H. A., "The Two-Quanta Hypothesis as a General Explanation for the Behavior of Threshold Values and Visual Acuity for the Several Receptors of the Human Eye." J. Opt. Soc. Amer. Vol. 38. July 1948. pp. 570-581.

3-17 Brindley, G. S., Spatial Summation in Colour-Receptive Pathways. Flying Personnel Research Committee Report No. 857, RAF Inst. of Aviation Medicine. December 1953.

3-18 Brindley, G. S., and Willmer, E. N., "The Reflexion of Light from the Macular and Peripheral Fundus Oculi in Man." J. Physiol. Vol. 116. 1952. pp. 350-356.

3-19 Brown, R. H., and Page, H. E., "Pupil Dilation and Dark Adaptation." J. Exp. Psychol. Vol. 25. October 1939. pp. 347-360.

3-20 Burnham, Robert W., "Binocular Subjective Colors and the Visual Mechanism." Amer. J. Psychol. Vol. 67. 1954. pp. 492-499.

3-21 Campbell, F. W., and Rushton, W. A. H., "Measurement of the Scotopic Pigment in the Living Eye." J. Physiol. Vol. 130. 1955. pp. 131-147.

3-22 Chatham, George N., "Entoptic Phenomena; An Interpretation of 'The Erythrocytes.' " Amer. J. Psychol. Vol. 63. 1950. pp. 612-615.

3-23 Crampton, George H., and Armington, John C., "Area-Intensity Relation and Retinal Location in the Human Electroretinogram." Amer. J. Physiol. Vol. 181. No. 1 April 1955.

3-24 Crozier, W. J., "On the Visibility of Radiation at the Human Fovea." J. Gen. Physiol. Vol. 34. September 20, 1950. pp. 87-136.

3-25 Crozier, W. J., and Holway, A. H., "Theory and Measurement of Visual Mechanisms. I. A Visual Discriminometer. II. Threshold Stimulus Intensity and Retinal Position." J. Gen. Physiol. Vol. 22. 1939. pp. 431-464.

3-26 Crozier, W. J., and Wolf, E., "On the Duplexity Theory of Visual Response in Vertebrates. II." Proc. Nat. Acad. Sci. Vol. 24. 1938. pp. 538-541.

3-27 Crozier, W. J., and Wolf, Ernst, "Temperature and the Critical Intensity for Response to Visual Flicker. III. On the Theory of the Visual Response Contour, and the Nature of Visual Duplexity." Proc. Nat. Acad. Sci. Vol. 25. 1939. pp. 171-175.

3-28 Crozier, W. J., and Wolf, Ernst, "Theory and Measurement of Visual Mechanisms. VIII. The Form of the Flicker Contour." J. Gen. Physiol. Vol. 25. 1942. pp. 369-379.

3-29 Crozier, W. J., and Wolf, Ernst, "Theory and Measurement of Visual Mechanisms. XII. On Visual Duplexity." J. Gen. Physiol. Vol. 2?. 1940. pp. 513-528.

3-30 Dzidzishvili, N. N., "The Influence of Intensity of Light Stimulation of One Eye on the Sensitivity of Discrimination of the Other." Translated by Robert Palmer. Psychol. Bull. Vol. 51. 1954.

3-31 Fry, Glenn A., and Alpern, Mathew, "The Effect on Foveal Vision Produced by a Spot of Light on the Sclera Near the Margin of the Retina." J. Opt. Soc. Amer. Vol. 43. March 1953. pp. 187-188.

3-32 Fry, Glenn A., and Alpern, Mathew, "Theoretical Implications of the Response of a Photoreceptor to a Flash of Light." Amer. J. Optom. and Arch. Amer. Acad. Optom. 1946. pp. 1-17.

3-33 Fry, Glenn A., and Robertson, V. M., "The Physiological Basis of the Periodic Merging of Area into Background." Amer. J. Psychol. Vol. 47. 1935. pp. 644-655.

3-34 Fugate, J. M., "Masking Technique for Isolating the Pupillary Response to Focused Light." J. Opt. Soc. Amer. Vol. 44. October 1954. pp. 771-779.

3-35 Fulton, J. F., (Editor), A Textbook of Physiology, Seventeenth Edition. W. B. Saunders Company, Philadelphia, Pa. 1947.

3-36 Garvey, C. R., "Is the Blind Spot Blind?" J. Exp. Psychol. Vol. 16. No. 1. pp. 83-97.

3-37 Graham, C. H., Vision:III. Some Neural Correlations: Handbook of Gen. Exp. Psychol. 1934. pp. 829-879.

3-38 Granit, Ragnar, Receptors and Sensory Perception. 1955.

3-39 de Groot, S. G., and Gebhard, J. W., "Pupil Size as Determined by Adapting Luminance." J. Opt. Soc. Amer. Vol. 42. 1952. pp. 492-495.

3-40 Harrison, E. R., "Visual Acuity and the Cone Cell Distribution of the Retina." Brit. J. Ophthal. Vol. 37. 1953. pp. 538-542.

3-41 Harrison, J., and Mayer, C., The Central Visual Mechanism. Boston University Optical Research Lab., Tech. Note 83. 1952.

3-42 Hartridge, H., Recent Advances in the Physiology of Vision. Blakiston Company, New York, N. Y. 1950.

3-43 Hecht, Selig, "Rods, Cones and the Chemical Basis of Vision." Physiol. Rev. Vol. 17. 1937. pp. 239-290.

3-44 Hecht, Selig, Shlaer, Simon, and Smith, Emil L., "Intermittent Light Stimulation and the Duplicity Theory of Vision." Cold Spring Harbor Symposia on Quant. Biol. Vol. 3. 1935. pp. 237-244.

3-45 Hess, E. H.," 'Subjective' Colors: Retinal Vs. Central Origin." Amer. J. Psychol. Vol. 65. 1952. pp. 278-280.

3-46 Houston, R. A., "Theory of Color Vision." J. Opt. Soc. Amer. Vol. 45. August 1955. pp. 589-592.

3-47 Hsia, Yun, and Graham, C. H., "Spectral Sensitivity of the Cones in the Dark Adapted Human Eye." Proc. Nat. Acad. Sci. Vol. 38. January 1952. pp. 80-85.

3-48 Hurvich, Leo M., and Jameson, Dorothea, "The Binocular Fusion of Yellow in Relation to Color Theories." Science. Vol. 114. August 24, 1951. pp. 199-202.

3-49 Jameson, Dorothea, and Hurvich, Leo M., "Some Quantitative Aspects of an Opponent-Colors Theory. I. Chromatic Responses and Spectral Saturation." J. Opt. Soc. Amer. Vol. 45. July 1955. pp. 546-552.

3-50 Keil, Francis C., Pupillary Size in Relation to Dark Adaptation. Project No. 16, Report No. 1. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. April 21, 1942.

3-51 Krieger, Howard P., and Bender, Morris B., "Dark Adaptation in Perimetrically Blind Fields." Arch. Ophthal. Vol. 46. 1951. pp. 625-636.

3-52 Kruger, Lawrence, and Boname, John R., "A Retinal Excitation Gradient in a Uniform Area of Stimulation." J. Exp. Psychol. Vol. 49. 1955. pp. 220-223.

3-53 Levine, Jacob, and Graham, C. H., "The Latency of Visual After-Effects as a Function of the Intensity of Illumination on an Adjacent Retinal Region." Amer. J. Psychol. Vol. 69. 1937. pp. 661-665.

3-54 Long, George E., "The Effect of Duration of Onset and Cessation of Light Flash on the Intensity-Time Relation in the Peripheral Retina." J. Opt. Soc. Amer. Vol. 41. November 1951. pp. 743-747.

"NOTICE: When Government or other drawings, specifications or other data are used for any purpose other than in connection wit a definitely related Government procurement operation, the U.S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulat furnished, or in any way supplied the said drawings, specifications or other data is not to be regarded by implication or otherwise a in any manner licensing the holder or any other person or corpor tion, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related theret

3-55 Ludvigh, Elek, and McCarthy, E. F., "Absorption of Visible Light by the Refractive Media of the Human Eye." Arch. Ophthal. Vol. 20. 1938. pp. 37-51.

3-56 Mandelbaum, Joseph, and Mintz, Ester U., "The Sensitivities of the Color Receptors as Measured by Dark Adaptation." Amer. J. Ophthal. Vol. 24. 1941. pp. 1241-1253.

3-57 Miles, Walter R., "Comparison of Functional and Structural Areas in Human Fovea. I. Method of Entoptic Plotting." J. Neurophysiol. Vol. 17. 1954. pp. 22-38.

3-58 Miles, W. R., "The Reaction Time of the Eye." Psychol. Monographs. Vol. 47. 1936. pp. 268-293.

3-59 Moss, Herbert L., and McDonald, Phillip R., The Effect of High Altitude on the Curvature of the Cornea. Project No. 61, Report No. 1. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. October 22, 1943.

3-60 Motokawa, Koiti, and Ebe, M., "The Physiological Mechanism of Apparent Movement." J. Exp. Psychol. Vol. 45. 1953. pp. 378-386.

3-61 Mueller, Conrad G., "A Quantitative Theory of Visual Excitation for the Single Photoreceptor." Proc. Nat. Acad. Sci., Vol. 40. Washington, D. C. September 1954. pp. 853-863.

3-62 Murray, Elsie, "Binocular Fusion and the Locus of 'Yellow'; Notes and Discussions." Amer. J. Psychol. Vol. 52. 1939. pp. 117-121.

3-63 O'Brien, Brian, and Miller, Norma D., A Study of the Mechanism of Visual Acuity in the Central Retina. Wright Air Development Center Tech. Report 53-198, University of Rochester, Aero Medical Laboratory Contract No. W33 (038)ac18317, RDO No. 694-45. May 1953.

3-64 Ogle, Kenneth N., "Optics and Visual Physiology." A.M.A. Arch. Ophthal. Vol. 47. June 1952. pp. 801-830.

3-65 Oikawa, Toshihiko, "Two Kinds of Scotopic Mechanisms in the Human Retina." Tohoku J. Exp. Medicine. Vol. 56. No. 1. 1955. pp. 69-81.

3-66 Oikawa, Toshihiko, and Kurosawa, Toshio, "The Behavior of Rods in Photopic Vision." Tohoku J. of Exp. Medicine. Vol. 60. No. 1. 1954. pp. 1-9.

3-67 Osterberg, G., "Topography of the Layer of Rods and Cones in the Human Retina." Acta Ophthalmol. Supplement. Vol. 61. 1935. pp. 1-102.

3-68 Pirenne, M. H., "Studies in the Physiological Mechanisms of Vision." Research. Vol. 2. June 1949. pp. 250-256.

3-69 Pirenne, M. H., "Physiological Mechanisms of Vision and the Quantum Nature of Light." Biological Reviews. Vol. 31. 1956. pp. 194-241.

3-70 Pirenne, M. H., Vision and the Eye. J. W. Arrowsmith Limited, Bristol, England. 1948.

3-71 Pirenne, M. H., and Denton, E. J. "Accuracy and Sensitivity of the Human Eye." Nature. Vol. 170. December 1952. pp. 1039-1047.

3-72 Pirenne, M. H., and Marriott, F. H. C., "Absolute Threshold and Frequency-of-Seeing Curves." J. Opt. Soc. Amer. Vol. 45. 1955. pp. 909-912.

3-73 Riopelle, Arthur J., and Bevan, William, Jr., "The Distribution of Scotopic Sensitivity in Human Vision." Amer. J. Psychol. Vol. 66. January 1953. pp. 63-80.

3-74 Riopelle, A. J., and Chow, K. L., "Scotopic Area-Intensity Relations at Various Retinal Locations." J. Exp. Psychol. Vol. 46. 1953. pp. 314-318.

3-75 Ross, Robert T., "A Comparison of the Regional Gradients of Fusion Frequency and Visual Acuity." Psychol. Monographs. Vol. 47. No. 212. 1936. pp. 306-310.

3-76 Ross, R. T., "The Fusion Frequency in Different Areas of the Visual Field: I. The Foveal Fusion Frequency II. The Regional Gradient of Fusion Frequency." J. Gen. Psychol. Vol. 15. 1936. pp. 133-147 and pp. 161-170.

3-77 Scofield, Carleton F., "Perception in the Region of the Optic Disk." Amer. J. Psychol. Vol. 42. April 1930. pp. 213-234.

3-78 Senders, Virginia L., "The Physiological Basis of Visual Acuity." Psychol. Bull. Vol. 45. 1948. pp. 465-490.

3-79 Sloan, L. L., "Rate of Dark Adaptation and Regional Threshold Gradient of the Dark-Adapted Eye: Physiologic and Clinical Studies." Amer. J. Ophthal. Vol. 30. June 1947. pp. 705-720.

3-80 Sloan, Louise L., "The Threshold Gradients of the Rods and the Cones: In the Dark-Adapted and in the Partially Light-Adapted Eye." Amer. J. Ophthal. Vol. 33. July 1950. pp. 1077-1089.

3-81 Smith, JoAnn, and Dimmick, F. L., The Parameters of Scotopic Sensitivity: (1) The Effect of Size. BuMed Project NM 003 041.09.09, Report 174. Medical Research Laboratory, U.S.N. Submarine Base, New London, Conn. June 1951. p. 10 and pp. 56-75.

3-82 Spring, K. H., and Stiles, W. S., Some Factors Affecting the Size of the Eye-Pupil. Great Britain, Dept. of Scientific and Industrial Research, National Physical Laboratory, Report No. PHOT. 3. 1947.

3-83 Stiles, W. S., (Editor), "Physiology of Vision." Brit. Med. Bull. Vol. 9. No. 1. 1953. pp. 1-84.

3-84 Stiles, W. S., "Visual Properties Studied by Subjective Measurements on the Colour-Adapted Eye." Brit. Med. Bull. Vol. 9. No. 1. 1953. pp. 41-50.

3-85 Stroud, John M., An Hypothesis of the Color Sensitivity of Cones. Talk delivered before Western Psychol. Assn.

3-86 Sulzman, John H., A Study of the Physiological Blind-Spot of the Dark-Adapted Fovea. U. S. Naval Submarine Base, Medical Research Laboratory Report No. 100, Progress Report No. 1 on Bur. of Med. Project X-492 (Av-262-p) and Bur. of Med. Project X-314 (Av-316-k). New London, Conn. March 1, 1946.

3-87 Talbot, Samuel A., "Green Vision and Binocular Fusion of Yellow." Science. Vol. 115. February 1952. pp. 220-221.

3-88 Thomson, L. C., "The Spectral Sensitivity of the Central Fovea." J. Physiol. Vol. 112. 1951. pp. 114-132.

3-89 Thomson, L. C., "Stimulation of the Retina With Light Fields of Small Size." Brit. Med. Bull. Vol. 9. 1953. pp. 50-55.

3-90 Travis, Roland C., "A Phenomenon in Vision Similar to Refractory Phase." Psychol. Monographs. Vol. 36. No. 10. 1926. pp. 1-17.

3-91 Van Den Brink, G., and Bouman, M. A., "Variation of Integrative Actions in the Retinal System: An Adaptational Phenomenon." J. Opt. Soc. Amer. Vol. 44. No. 8. 1954. pp. 616-620.

3-92 De Vries, Hl., "Concentration of Visual Purple in the Human Eye." Nature. Vol. 158. 1946. p. 303.

3-93 Wagman, Irving H., U. S. Office of Scientific Research and Development, National Defense Research Committee, O.S.R.D. No. 6098. Sect. 16.1, Report No. 134, Contract OEMsr-1226, University of Pennsylvania, Johnson Foundation. October 15, 1945.

3-94 Wald, George, "Human Vision and the Spectrum." Science. Vol. 101. June 29, 1945. pp. 653-658.

3-95 Wallach, Hans, and Adams, Pauline Austin, "Binocular Rivalry of Achromatic Colors." Amer. J. Psychol. Vol. 67. 1954. pp. 513-516.

3-96 Wallach, Hans, and Austin, Pauline, "Recognition and the Localization of Visual Traces." Amer. J. Psychol. Vol. 67. 1954. pp. 338-340.

3-97 Walls, Gordon L., "The Filling-in Process." Amer. J. Optom. and Arch. Amer. Acad. Optom. Vol. 31. July 1954. pp. 329-340.

3-98 Walls, G. L., The Vertebrate Eye and Its Adaptive Radiation. Cranbrook Press, Bloomfield Hills, Conn. 1942.

3-99 Weale, R. A., "Colour Vision in the Peripheral Retina." Brit. Med. Bull. Vol. 9. No. 1. 1953. pp. 55-61.

3-100 Wulff, V. J., Electrophysiology of the Visual Pathway. Contract N-onr-63905, Inst. of Industrial Research, Annual Progress Report, Sept. 15 to Dec. 31, 1952; ASTIA Document No. AD-25 867, Title Announcement Bull. U-63: 48. Syracuse, N. Y. November 12, 1954.

CHAPTER 4

OPTICS OF THE EYE

For clear vision, the eye must refract most of the light received from each point on an object so as to focus it on a corresponding point on the retina. The eye has many refracting surfaces, but the most important are at the cornea, where the greatest refraction occurs, and at the lens, whose curvature can be changed for fine adjustments in focusing. For most purposes, the complex optical system of the eye can be described in terms of a reduced eye (reduced from the normal eye) with a single hypothetical refracting surface. A study of the optics of the eye shows that when the normal eye is at rest, rays that are not parallel--that is, rays from any point closer than infinity--are focused behind the retina. However, light rays from points farther than about 6 meters are nearly enough parallel so that the eye perceives a sharp image without adjusting. For closer objects, the eye converges light rays on the retina by increasing the curvature of the lens, a process called accommodation. The sharpness of an image can also be increased by reducing pupil size or looking through a small aperture. Much of the light entering the eye is scattered or absorbed; scattered light falling on the retina tends to reduce the contrast between the image and the field around it.

When the two eyes are fixated on a distant object, the visual axes are almost parallel in most individuals. To bring the images of near objects to corresponding points on the two retinas, and avoid a double image, the eyes are turned toward each other, so that the visual axes converge on the object. The eyes also move in unison to keep the images of moving objects in the field of vision, or to scan the field; they move in short jumps, called saccadic movements, with clear vision occurring between jumps.

OPTICS OF THE NORMAL EYE

Refraction in the Eye

For an object to be seen clearly, the light rays entering the eye from any point on the object must be brought to focus on a corresponding point in the retina. The eye focuses light by <u>refracting</u> it -- bending it as it enters the eye and passes through to the retina. The degree to which light is refracted when passing from one medium to another depends on (1) the index of refraction of one medium relative to the other, (2) the curvature of the surface between them, and (3) the angle at which light strikes the surface (see Chapter 2).

From the air, which has a refractive index of 1.00, light enters the eye through the cornea (refractive index 1.376), then passes successively through the aqueous humor (refractive index 1.336), the crystalline lens (1.42), and the vitreous humor (1.336). The greatest difference in indexes of refraction is between the outer air and the cornea, which in addition is sharply curved. Therefore, the greatest amount of refraction in the ocular system occurs when the light enters the cornea from the air. The cornea does the primary job of converging light toward the retina, while changes in the crystalline lens serve as a fine adjustment to sharpen the images of near objects.

The Reduced Eye

It would be difficult to trace a light ray accurately from the point where it enters the cornea to the point where it stimulates the retina. One would have to compute its refraction at each surface of both the cornea and the crystalline lens, not to mention the minute changes at the surfaces of the layers within these structures.

However, a simple optical system can be postulated that will match the optical path of the eye closely enough for most purposes. This system, the <u>reduced eye</u>, averages the components of the ocular system; light entering it will reach virtually the same final position on the retina as in the true eye. The reduced eye is an ideal convex spherical surface with a radius of curvature of 5.73 mm; this surface, the <u>hypothetical refracting surface</u>, separates two media whose refractive indexes are 1.00 and 1.336, respectively. Its anterior focal length is 17.054 mm and its posterior focal length is 22.78 mm. (The posterior focal point falls at the retina in the normal eye.) This hypothetical refracting surface lies 1.35 mm behind the front of the cornea.

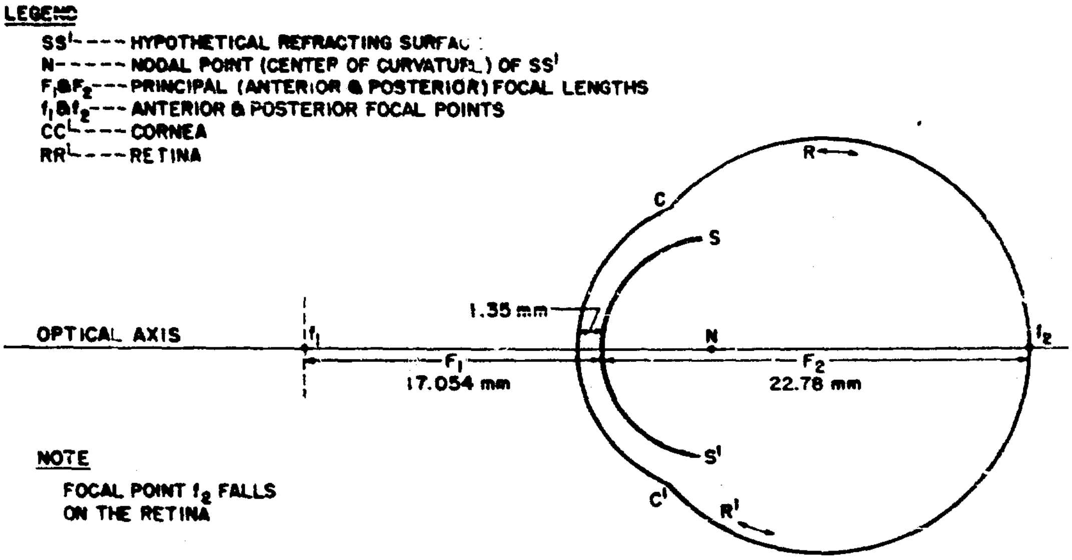


Figure 4.1. The Reduced Eye (Scale 2.5:1)

Figure 4.1 shows the reduced eye and its relation to the real eye. Certain rays can be traced through the reduced eye in accordance with the following rules:

1. Rays arriving at SS' while traveling parallel to the optical axis will all be bent so that they pass through the posterior focal point, f_2, on the retina.

2. Rays arriving at SS' from the anterior focal point, f_1, will be bent so that they are parallel to the optical axis.

3. Rays traveling directly toward the center of the spherical surface, nodal point N, will pass straight through the system undeflected.

Figure 4.2A shows how these rules apply to a normal resting eye. Consider first three of the rays emanating from the tip of the arrow representing the object. The first ray (1) is parallel to the optical axis; at the surface SS' it will be bent to pass through f_2 (rule 1). The second ray (2) passes through f_1 to SS', where it is bent so as to parallel the optical axis (rule 2). Where rays 1 and 2 meet, we will have an image of the tip. To check the solution, assume that ray 3 passes through the nodal point, N: It passes undeflected through SS' (rule 3) and meets rays 1 and 2 at their junction. In the perfect eye, all rays emanating from the tip of the object and entering the eye would converge to form an image of the tip at this point, but we can determine the image point by simply tracing two lines that follow any two of our three rules. Now, since the base of the object lies on the optical axis, which passes undeflected through N (rule 3), the base of the image will also lie on the axis. The complete image can therefore be represented by a perpendicular arrow drawn from the axis to the intersection of the rays emanating from the tip of the object.

Note that the image is inverted within the eye. We do not perceive an inverted world, however, because the experience of seeing takes place within the brain, not at the retina; the inversion at this way-station of the visual path is incidental to the final perception.

In Figure 4.2B, the object has been moved farther from the eye. Note that the image has now moved in closer to f_2, which lies on the retina. For an image to move in all the way to f_2, however, the object would have to be moved an infinite distance away, so that all rays reaching the eye from the object would be parallel to the optical axis. Thus, Figure 4.2 shows that the eye at rest is focused for infinity; actual objects, at finite distances, will appear blurred, because their images fall behind the retina. When the object is farther than about 20 feet from the eye, however, the effect of blur is slight and the eye can tolerate it. For closer objects, the eye adjusts its focus by changing the curvature of the refracting surfaces.

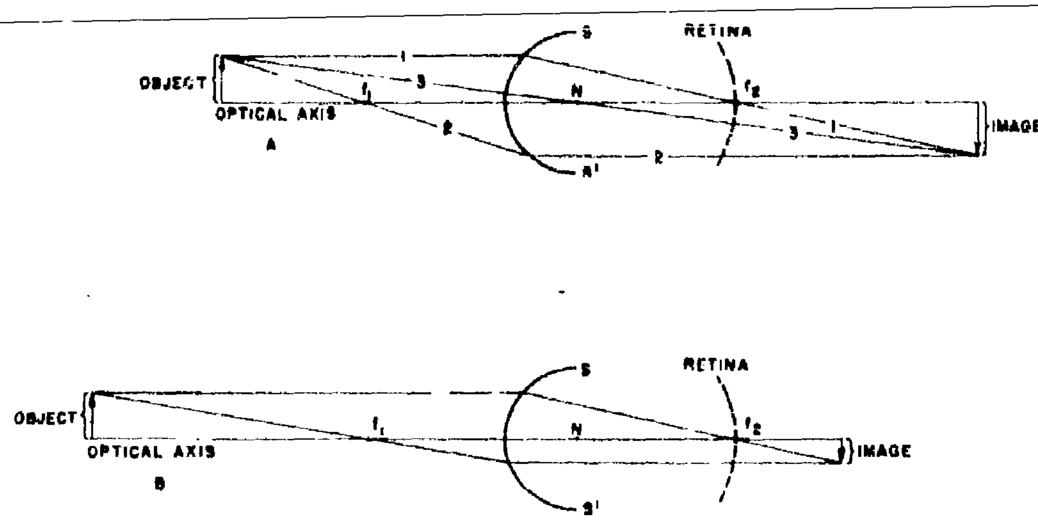


Figure 4.2 How Light Rays From Objects are Bent at Hypothetical Refracting Surface (S S') to Form Image in Normal Resting Eye

The image of the farther object (B) is closer to focal point f_2 on the retina, but both images are behind retina and appear blurred.

Depth of Field

Consider first the situation for more distant objects. Figure 4.3 shows image I_1 for a close object O_1, image I_2 for a farther object O_2, and the cones of the light rays from each object that are intercepted and refracted by the hypothetical refracting surface. (The retina, for this purpose may be considered a plane.) The image of each object is in focus behind the retina; on the retina itself it appears as a circle, called a blur circle. As the object is moved farther away, the blur circle becomes smaller. At about six meters, the circle, while not infinitely small, is small enough so that the brain interprets it as a point. Thus, it might be said that for objects beyond six meters, the physical deviations from true focus on the retina are within the limits of accuracy of the brain's perceptive powers, when the eye is focused for infinity; or as visual scientists express it, the resting eye has a depth of field of six meters (20 feet) to infinity.

While still focused for infinity, the eye can sharpen visual images further by reducing the size of the pupil -- the opening in the iris just outside the crystalline lens (see Chapter 3). Figure 4.4 shows schematically how reducing the pupil reduces the blur circle. The dashed lines outline the cone of rays that would be intercepted and bent by the refracting surface if there were nothing between object and eye. The solid lines outline the reduced cone obtained by limiting vision to the small pupillary opening. In the second case, the focus on the retina is much sharper. Visual images can also be sharpened by squinting and by looking through a small hole, such as a pinhole. The advantages of all these procedures, of course, may be outweighed by the loss of light that reaches and stimulates the eyes.

Accommodation

In order that objects closer than six meters may be brought to focus on the retina, the optical system of the eye must be modified. This is accomplished by contracting the ciliary muscles that allow the crystalline lens to become more convex. This process, called accommodation, is illustrated in Figure 4.5. In Figure 4.5A, the eye is at rest -- focused for infinity; the image of the close object is brought to focus well back of the retina, and its retinal image is blurred. In Figure 4.5B, the eye is accommodated; the crystalline lens becomes more convex so that the image falls on the retina.

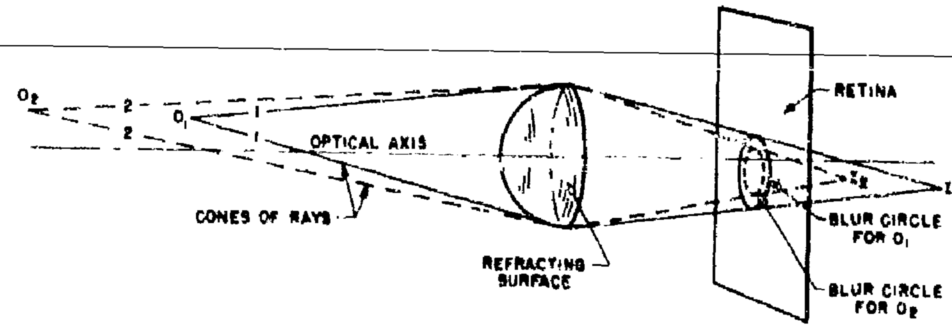


Fig. 4.3 Blur Circles Produced on the Retina by Two Objects O_1 and O_2, at Different Distances From the Eye

The farther object has a smaller blur circle, and its image on the retina is more nearly in focus.

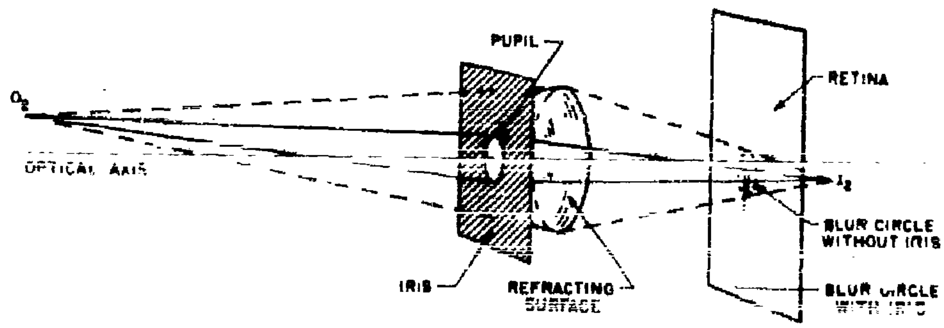


Figure 4.4 How the Blur is Reduced by an Obstruction, Such as the Iris, That Limits the Spread of Light Rays Reaching the Eye

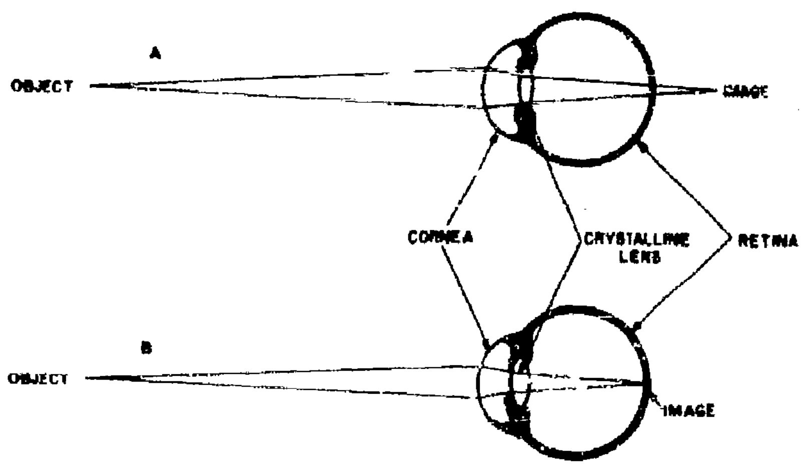


Figure 4.5 How the Eye Accommodates to Focus on Near Objects

In A, the eye is at rest -- focused for infinity. In B, the curvature of the crystalline lens is increased; the rays from the object are bent more, and the image is brought to the retina.

The amount of accommodation exerted by the eye is expressed in diopters, the unit used for designating the refractive power of a lens. The power of a lens in diopters is the reciprocal of its focal length in meters ($D = 1/F$). A one-diopter lens focuses parallel rays at a point one meter away, while a four-diopter lens focuses parallel rays at a point one-quarter meter away. You will recall that the unaccommodated eye is in focus for parallel rays. If a four-diopter lens is placed before the unaccommodated eye, an object one-quarter meter away will be focused on the retina. Therefore we can say that, if the crystalline lens of the eye accommodates to an equivalent extent, its focusing power has increased by four diopters over its unaccommodated state. In other words, the amount of accommodation of the eye for an object at a given distance is the refractive power of the lens that would have to be placed in front of the unaccommodated eye to bring the same object into focus.

Scattering and Absorption of Light in the Eye

Light passing through the eye from cornea to retina is absorbed and scattered at the surface of each component of the eye and in each medium through which it passes. It has been estimated from experimental data that only 10 percent of light incident on the cornea actually gets through to stimulate the visual receptors. Obviously, the individual receptors must be very sensitive for vision to occur. They are probably almost perfect detectors, able to respond to almost the smallest amounts of energy that can be brought to them.

A sizable amount of the scattered or "stray" light reaches and stimulates the retina outside the region on which the image falls. Because of this stray light, electrical measurements sometimes show a greater total response from the receptors outside the image than in it -- though the response outside the image is less concentrated, being divided amongst a multitude of receptors. The effect of stray light is to reduce the contrast -- the difference in intensity -- between the image and the visual field around it. This reduction in contrast can reduce one's ability to distinguish an object, as will be seen in Chapter 6.

Vision with Both Eyes

Up to this point, we have been talking about vision in a single eye (monocular vision). The structure and optics are essentially the same for each of the two eyes. However, when the two eyes are working together (binocular vision), additional characteristics come into play.

When the eyes are at rest, their visual axes are parallel, in most individuals, and the images of distant objects fall on corresponding points in the two retinas. However, as an object approaches the resting eye, the relative locations of the two retinal images tend to change, and the person sees a double image. To compensate, he turns the two eyes toward each other, so that the visual axes cross at the approaching object, whose image thus remains on corresponding points on the two retinas. This procedure is called convergence.

The two eyes also coordinate in other ways. As an object moves laterally and vertically, the two eyes move in unison to keep it in the field of vision. (Note that this is a different kind of coordination from convergence.) The eyes coordinate in the same way when they have no definite object on which to focus -- when they are moved together to search for details on the visual field. For example, the eyes move in unison when a person is reading an instrument panel or searching the sky or land surface for a target. Since a fixed object would appear as a blurred image in a moving eye, the eyes scan a field in a series of short jumps; clear vision occurs when they are stationary between jumps. These jerky motions (saccadic movements) must occur in unison in the two eyes, but with a correction in each eye for convergence. In addition, the pupils of the two eyes are adjusted in unison, and their crystalline lenses change curvature to the same degree to keep near objects in focus. Thus it can be seen that in normal vision convergence, saccadic motions, and pupillary and lens adjustments are occurring simultaneously in an integrated manner.

GENERAL BIBLIOGRAPHY

4-1 Anon. Technical Optics. Imperial College of Science and Technology, London, England.

4-2 Abelès, F., New Method for the Rapid Determination of the Approximate Values of Optical Constants and Thickness of a Thin Absorbing Layer. 1954.

4-3 Ames, A., Jr., Gliddon, Gordon H., and Ogle, Kenneth N., "The Importance of the Relative Size and Shape of Ocular Images in Vision." Annals of the Distinguished Service Foundation of Optometry. 1932. pp. 12-26.

4-4 Ames, A., Jr., Gliddon, Gordon, H., and Ogle, Kenneth N., "Lenses for Changing the Size and Shape of Dioptric Images." Annals of the Distinguished Service Foundation of Optometry. 1932. pp. 27-36.

4-5 Ames, Adelbert, Jr., and Ittelson, William H., "Accommodation, Convergence, and Their Relation to Apparent Distance." J. Psychol. Vol. 30. 1950. pp. 43-62.

4-6 Ames, A., Jr., and Ogle, Kenneth N., "The Horopter and Corresponding Retinal Points." Annals of the Distinguished Service Foundation of Optometry. 1932. pp. 1-11.

4-7 Ballard, Stanley, A Bibliography on Reflecting Optics Covering the Period 1925-1950. Armed Forces-National Research Council Vision Committee. November 1950. Supplement, March 15, 1951.

4-8 Bartlett, Neil R., and Gagne, R. M., On Binocular Summation at Threshold. 1939.

4-9 Bartley, S. H., "Conditions Intended to Manipulate Accommodation as Factors in Performance with a Visual Acuity Target." J. Psychol. Vol. 36. 1953. pp. 409-415.

4-10 Beck, Lloyd Henry, "A Functional Interpretation of the Stiles-Crawford Effect." J. Opt. Soc. Amer. Vol. 43. October 1953. p. 924.

4-11 Blum, H. F., and Fisher, M. B., U. S. Naval Medical Research Institute, Research Project X-254. May 25, 1944. (CONFIDENTIAL)

4-12 Bouman, M. A., "On Foveal and Peripheral Interaction in Binocular Vision." Werkgroep Waarneming, Rapport No. WW 1953-11. Opt. Acta. Vol. 1. No. 4. 1955. pp. 177-182.

4-13 Brozek, J., Somonson, E., Bushard, W. J., and Peterson, J. H., "Effects of Practice and the Consistency of Repeated Measurements of Accommodation and Vergence." Amer. J. Ophthal. Vol. 31. 1948. pp. 191-198.

4-14 Chapanis, A., Garner, W. R., and Morgan, C. T., Applied Experimental Psychology, Human Factors in Engineering Design. John Wiley and Sons, New York, N. Y. 1949.

4-15 Cibis, Paul A., Gerathewohl, Siegfried, J., and Rubinstein, David. Depth Perception in Monocular and Binocular Vision. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. January 1953.

4-16 Dusek, R. D., Teichner, W. H., and Kobrick, J. L, Effects of the Angular Relationships between the Observer and the Base-Surround of the Stimuli on Relative Depth Discrimination. Report No. 232. Headquarters Quartermaster Research and Development Center, Natick, Mass. June 1954.

4-17 Fincham, E. F., "Factors Controlling Ocular Accommodation." Brit. Med. Bull. Vol. 9. No. 1. 1953. pp. 18-22.

4-18 Fry, Glenn A., "Blurredness of the Retinal Image." Optometric Weekly. October 31, 1946.

4-19 Fry, Glenn A., "Fundamental Variables in the Relationship between Accommodation and Convergence." Optometric Weekly. March 18-25, 1943; Optical Developments. Vol. 20. No. 1. January 1950. pp. 1-6. (Riggs Optical Co., Chicago, Ill., Publisher).

4-20 Fry, Glenn A., "The Relationship between Geometrical Perspective and Stereo Cues." Amer. J. Optom. and Arch. Amer. Acad. Optom. Vol. 29. July 1952. pp. 353-368.

4-21 Fry, Glenn A., "Visual Perception of Space." Amer. J. Optom. and Arch. Amer. Acad. Optom., Monograph. No. 110. November 1950.

4-22 Fry, Glenn A., and Bartley, S. H., "The Brilliance of an Object Seen Binocularly." Amer. J. Ophthal. Vol. 16. 1933. pp. 687-693.

4-23 Gilinsky, Alberta S., A Review of Literature on the Relative Efficiency of the Dominant and the Nondominant Eye. WADC Tech. Report 52-13. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. January 1952.

4-24 Graham, C. H., "Visual Space Perception." Federation Proc. Vol. 2. 1943. pp. 115-122.

4-25 Grether, Walter F., "Comparative Visual Acuity Thresholds in Terms of Retinal Image Widths." J. Compar. Psychol. Vol. 31. No. 1. February 1941. pp. 23-33.

4-26 Hardy, A. C., and Perrin, F. H., The Principles of Optics. McGraw-Hill Book Company. Inc., New York, N. Y. 1932.

4-27 Hardy, LeGrand H., Rand, Gertrude, Rittler, M. Catherine, Blank, Albert A., and Boeder, Paul, The Geometry of Binocular Space Perception. Institute of Ophthalmology, Columbia University, College of Physicians and Surgeons, and Office of Naval Research, Contract N6onr-27119, NR 143-638.

4-28 Heavens, O. J., Optical Properties of Thin Solid Films. Academic Press, New York, N. Y.; Butterworth, London, England. 1955.

4-29 von Helmholtz, H., Helmholtz's Treatise on Physiological Optics. Vol. 1. (in English). Translation by J. P. C. Southall, Optical Society of America. 1924.

4-30 von Helmholtz, H., Helmholtz's Treatise on Physiological Optics. Vol. 2. The Sensations of Vision (in English). Translation by J. P. C. Southall, Optical Society of America. 1924.

4-31 von Helmholtz, H., Helmholtz's Treatise on Physiological Optics. Vol. 3. (in English). Translation by J. P. C. Southall, Optical Society of America. 1925.

4-32 Hermans, Thomas C., "The Perception of Size in Binocular, Monocular, and Pinhole Vision." J. Exp. Psychol. Vol. 27. No. 2. August 1940. pp. 203-207.

4-33 Hermans, Thomas C., "The Relationship of Convergence and Elevation Changes to Judgments of Size." J. Exp. Psychol. Vol. 48. 1954. pp. 204-208.

4-34 Hofstetter, H. W., "Accommodation, Convergence, and Their Relation to Apparent Distance: A Criticism." J. Psychol. Vol. 30. 1950. pp. 393-394.

4-35 Hofstetter, H. W., "Optometric Contributions in Accommodation and Convergence Studies." J. Amer. Optom. Assoc. Vol. 25. No. 8. March 1954. pp. 431-439.

4-36 Hofstetter, H. W., "The Relationship of Proximal Convergence to Fusional and Accommodative Convergence." Amer. J. Optom. Vol. 28 1951. pp. 300-308.

GENERAL BIBLIOGRAPHY (Cont)

4-37 Imus, Henry A., The State of Accommodation of the Human Eye in Darkness. Tech. Report ONRL-9-52. Office of Naval Research, London, England. January 30, 1952.

4-38 Ishak, I. G. H., Hefzalla, I. M. H., and Badawy, Y. K. M., "Role of Convergence in Stereoscopic Vision." J. Opt. Soc. Amer. Vol. 46. 1956. p. 303.

4-39 Karwoski, Theodore F., and Lloyd, V. V., "Studies in Vision: V. The Role of Chromatic Aberration in Depth Perception." J. Gen. Psychol. Vol. 44. 1951. pp. 159-173.

4-40 Koomen, M., Tousey, R., and Scolnik, R., "The Spherical Aberration of the Eye." J. Opt. Soc. Amer. Vol. 39. 1949. pp. 370-376.

4-41 Lapicque, Charles, "Optics of the Eye and Form Perception." Revue d'Optique (theorique et instrumentals). Vol. 17. No. 9. 1938. pp. 297-318.

4-42 Leibowitz, H., "The Effect of Pupil Size on Visual Acuity for Photometrically Equated Test Fields at Various Levels of Luminance." J. Opt. Soc. Amer. Vol. 42. June 1952. pp. 416-422.

4-43 Leibowitz, H., "Some Observation and Theory on the Variation of Visual Acuity with the Orientation of the Test Object." J. Opt. Soc. Amer. Vol. 43. October 1953. pp. 902-905.

4-44 Linfoot, E. H., "Information Theory and Optical Images." J. Opt. Soc. Amer. Vol. 45. 1955. pp. 808-819.

4-45 Linksz, A., Physiology of the Eye. Vol. 1. Optics. Grane and Strotton, New York, N. Y. 1950.

4-46 Luckiesh, Matthew, and Moss, Frank K., "Refraction of Various Spectral Qualities of Light by the Human Eye." J. Opt. Soc. Amer. Vol. 31. September 1941. pp. 595-597.

4-47 Luneburg, Rudolf K., "The Metric of Binocular Visual Space." J. Opt. Soc. Amer. Vol. 40. October 1950. pp. 627-642.

4-48 Lyle, Donald J., Neuro-Ophthalmology, Second Edition. Charles C. Thomas, Springfield, Ill. 1945.

4-49 McFadden, H. B., Three Studies in Psychological Optics. Optometric Extension Program, Duncan, Okla. 1941. (Thesis, Ohio State University) 1940.

4-50 Morgan, Joseph, Introduction to Geometrical and Physical Optics. McGraw-Hill Book Company, Inc., New York, N. Y. 1953.

4-51 Ogle, K. N., "Basis of Stereoscopic Vision." A.M.A. Arch. Ophthal. Vol. 52. 1954. pp. 197-211.

4-52 Ogle, K. N., "Disparity Limits of Stereopsis." Arch. Ophthal. Vol. 48. July 1952. pp. 50-60.

4-53 Ogle, K. N., "Fixation Disparity." Amer. Orthopt. J. Vol. 4. June 1954. pp. 35-39.

4-54 Ogle, K. N., "On the Limits of Stereoscopic Vision." J. Exp. Psychol. Vol. 44. 1952. pp. 253-259.

4-55 Ogle, K. N., "On the Resolving Power of the Human Eye." J. Opt. Soc. Amer. Vol. 41. 1951. pp. 517-520.

GENERAL BIBLIOGRAPHY (Cont)

4-56 Ogle, K. N., "Precision and Validity of Stereoscopic Depth Perception from Double Images." J. Opt. Soc. Amer. Vol. 43. 1953. pp. 906-913.

4-57 Ogle, K. N., "Stereopsis and Vertical Disparity." A.M.A. Arch. Ophthal. Vol. 53. 1955. pp. 495-504.

4-58 Ogle, K. N., "Stereoscopic Acuity and the Role of Convergence." J. Opt. Soc. Amer. Vol. 46. 1956. pp. 269-273.

4-59 Ogle, K. N., "On Stereoscopic Depth Perception." J. Exp. Psychol. Vol. 48. October 1954. pp. 225-233.

4-60 Peckham. R. H., "Eye Movements during Retinal Rivalry." Amer. J. Psychol. Vol. 48. January 1936. pp. 43-63.

4-61 Pratt, Cornelia, and Dimmick, Forrest L., An Ophthalmological Study of Visual Acuity under Dim Illumination. U. S. Naval Submarine Base, New London, Conn. Medical Research Laboratory Report No. 173. Vol. 10. 1951. pp. 42-55. Bur. of Med. Project NM 003 041.04.04. June 6, 1951.

4-62 Purdy, D. M., "The Structure of the Visual World: II. The Action of Motor Impulses on Sensory Excitations." Psychol. Rev. Vol. 42. No. 6. November 1935. pp. 528-536.

4-63 Rady, A. A., and Ishak, I. G. H., "Relative Contributions of Disparity and Convergence to Stereoscopic Acuity." J. Opt. Soc. Amer. Vol. 45. No. 7. July 1955. pp. 530-534.

4-64 Ratliff, Floyd, "The Role of Physiological Nystagmus in Monocular Acuity." J. Exp. Psychol. Vol. 43. March 1952. pp. 163-172.

4-65 Ratliff, Floyd, and Riggs, Lorrin A., "Involuntary Motions of the Eye during Monocular Fixation." J. Exp. Psychol. Vol. 40. December 1950. pp. 687-701.

4-66 Riggs, Lorrin A., Armington, John C., and Ratliff, Floyd, "Motions of the Retinal Image during Fixation." J. Opt. Soc. Amer. Vol. 44. April 1954. pp. 315-321.

4-67 Riggs, Lorrin A., and Ratliff, Floyd, "Visual Acuity and the Normal Tremor of the Eyes." Science. Vol. 114. 1951. pp. 17-18.

4-68 Sears, Francis W. Principles of Physics. III. Optics. Addison-Wesley Publishing Company, Reading, Mass. 1949.

4-69 Sloan, Louise L., "Comparison of the Nagel Anomaloscope and Dichroic Filter Anomaloscope." J. Opt. Soc. Amer. Vol. 40. 1950. pp. 41-47.

4-70 Sloan, Louise L., "Measurement of Visual Acuity." Arch. Ophthal. Vol. 45. 1951. pp. 704-725.

4-71 Tiffin, Joseph, Miller, Gilbert E., and Chew, William B., The Development and Evaluation of a Methodology for Establishing Visual Requirements for Naval Personnel. U. S. Navy, Office of Naval Research, Bureau of Naval Personnel, Personnel Analysis Division. Tech. Bull. 53-7. 1953.

4-72 Tinker, Miles A., "Involuntary Blink Rate and Illumination Intensity in Visual Work." J. Exp. Psychol. Vol. 39. 1949. pp. 558-560.

4-73 Tuttle, M. J., Estimation and Control of Light Levels Used for Night Vision Testing. Nat'l Research Council of Canada, Assoc. Committee on Army Med. Research, C6110.

4-74 **Valasek**, Joseph, Introduction to Theoretical and Experimental Optics. 1949.

4-75 **Verplanck, W. S.,** Comparative Study of Adaptometers. U. S. Naval Submarine Base, New London, Conn. Medical Research Laboratory Report No. 10. December 1, 1942.

4-76 **Verplanck, W. S.,** and Reed, D. T., A Report on the Test-Retest Reliability of the Admiralty Mark I Adaptometer. U. S. Naval Submarine Base, New London, Conn. Medical Research Laboratory Report No. 16. February 1943.

4-77 Verplanck, W. S., and Reed, D. T., U. S. Naval Submarine Base, New London, Conn. Medical Research Laboratory. 1943. (CONFIDENTIAL)

4-78 Verplanck, W. S., and Reed, D. T., A Report on the Test-Retest Reliability of the Wright Adaptometer. U. S. Naval Submarine Base, New London, Conn. Medical Research Laboratory Report No. 18. March 5, 1943.

4-79 Verplanck, W. S., Watson, G. E., and Reed, D. T., Field Tests of the Radium Plaque Adaptometer. U. S. Naval Submarine Base, New London, Conn. Medical Research Laboratory Report No. 33. November 26, 1943.

4-80 Volk, David, and Fry, Glenn A., "Effect of Quality of Illumination and Distance of Observation upon Performance in the Ishihara Test." Amer. J. Optom. and Arch. Amer. Acad. Optom. Monograph 24. March 1947.

4-81 Walburton, F. L., Variations in Normal Colour Vision in Relation to Practical Colour Matching. June 1, 1954.

4-82 Wald, George, and Griffin, Donald R., "The Change in Refractive Power of the Human Eye in Dim and Bright Light." J. Opt. Soc. Amer. Vol. 37. May 1947. pp. 321-336.

4-83 Walls, Gordon L., "A Theory of Ocular Dominance." A.M.A. Arch. Ophthal. Vol. 45. April 1951. pp. 387-412.

4-84 Westheimer, Gerald, "Eye Movement Responses to a Horizontally Moving Visual Stimulus." A.M.A. Arch. Ophthal. Vol. 52. 1954. pp. 932-941.

4-85 Westheimer, Gerald, "Mechanism of Saccadic Eye Movements." A.M.A. Arch. Ophthal. Vol. 52. 1954. pp. 710-723.

4-86 Westheimer, Gerald and Conover, Donald W., "Smooth Eye Movements in the Absence of a Moving Visual Stimulus." J. Exp. Psychol. Vol. 47. No. 4. April 1954.

4-87 Weston, H. C., Sight, Light, and Efficiency. 1949.

4-88 Willis, M. P. and Farnsworth, Dean, Comparative Evaluation of Anomaloscopes. U. S. Naval Submarine Base, New London, Conn. No. 7. Report No. 190. August 15, 1952. BuMed & Surg., Navy Dept., Project NM003 041 26.01.

4-89 Yarbus, A. L., "A Research on the Laws of Eye Movement in Vision." Dokl. Akad. Mauk. Vol. 96. No. 4. 1954. pp. 733-735.

4-90 Zoethout, W. D., Physiological Optics. Professional Press, Chicago, Ill. 1947.

CHAPTER 5

REFRACTIVE ERRORS, HETEROPHORIA, AND HETEROTROPIA

This chapter is divided into three sections. The first deals with refractive errors and impairment of optical functions due to increasing age. The second deals with potential and actual loss of fixation of one of the eyes -- heterophoria and heterotropia. The third gives current visual standards for flying personnel.

A refractive error exists when, with the lens inside the eye in the resting state (least convex), parallel rays of light are not focused on the retina. There are three ways the refractive surfaces of the eye can fail to focus parallel rays. First, the rays may be focused in front of the retina; this is myopia. Second, the rays may be focused behind the retina; this is hyperopia. Third, the rays may be focused unevenly in relation to the plane of the retina; this is astigmatism.

In addition to these three types of refractive errors that exist with the eye in a resting state, there is a fourth condition that occurs with increasing age and is due to the diminishing ability of the eye lens to increase its convexity. This diminishing ability to increase its convexity results in the failure to bring the diverging rays from near objects to a focus on the retina; this is presbyopia.

Correction of refractive errors is provided by spectacle type lenses or contact lenses. Spectacle type lenses are better than contact lenses for most flying personnel. Contact lenses are indicated only in specific cases. Contact lenses are, in most cases, unsatisfactory because of one severe disadvantage. This disadvantage is the inability of most wearers to tolerate the contact lenses for more than a very few hours at a time.

Heterophoria is the tendency of the visual axes of the two eyes to deviate from parallelism when there is no stimulus for fusion -- i.e., when the observer has no definite object to look at. Heterotropia exists when the deviation from parallelism is not overcome even when a stimulus is present. The result is a double image, until the development of suppression of vision in the deviating eye.

While most people have some heterophoria, the condition can cause symptoms such as eyestrain and headaches; it can lead to temporary heterotropia during periods of stress in the air (high g-forces, hypoxia, etc.); it may develop into permanent heterotropia, or cause difficulty in distance judgment in landing. While the last result has been the chief justification for rejecting applicants for flying and for grounding flying personnel who have marked heterophoria, both theory and experience indicate that too much importance has been attached to the effect of heterophoria on landing. In general, standards should be based on (a) the probability of any decrease in flight performance that may result from any of the symptoms of heterophoria and (b) the likelihood that heterophoria may develop into heterotropia.

In the last section of the chapter, current U. S. Air Force standards are presented for pilots and other flight personnel.

REFRACTIVE ERRORS

In the normal eye, when the eye is at rest, parallel rays are focused on the retina. However, a large percentage of the population has an optical system in one or both eyes such that, with the lens at rest, parallel rays are not focused on the retina. They have myopia (nearsightedness), hyperopia (farsightedness), or astigmatism (unsymmetrical curvature of refractive surfaces). A fourth defect, presbyopia, a gradual loss of ability to focus for near objects, affects all eyes according to increasing age.

Types of Refractive Errors

If, with the lens of the eye at rest (least convex), parallel rays are brought to a focus on the retina, then there is no refractive error, and the eye is called normal, or emmetropic (Fig. 5.1). If parallel rays are not brought to a focus on the retina when the eye is at rest, a refractive error, or ametropia, exists. This ametropia is due to the fact that the focusing power of the cornea and lens does not conform to the distance from the lens to the retina[5-1, 5-3, 5-10] If parallel rays are brought to a focus in front of the retina, when the eye lens is at rest, myopia, or nearsightedness, exists. In this case, the too convex lens will focus the diverging rays from near objects on the retina, but not parallel rays. The result is an inability to see distinctly objects more distant than the conjugate focal point of the retina (f_c, Fig. 5.1). Myopia ordinarily does not produce symptoms of eyestrain; the individual just does not see distinctly.[5-1, 5-3]

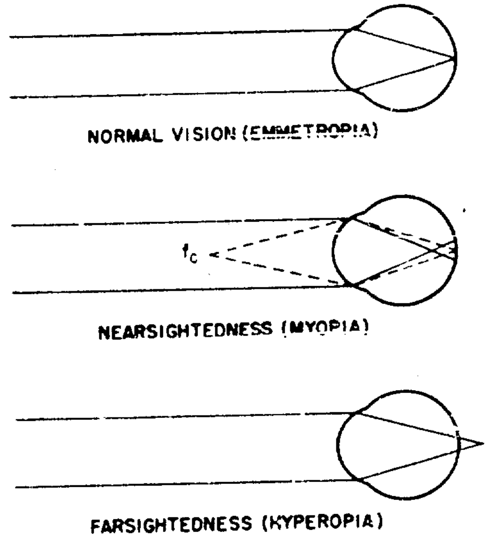


Figure 5.1 Schematic Showing Relation of Image to Retina of Eye at Rest for Normal Vision and Two Types of Refractive Errors

If parallel rays are focused behind the retina, when the eye lens is at rest, hyperopia, or farsightedness, exists (Fig. 5.1). Unless the lens has lost its focusing power with increasing age, or the hyperopia is excessive, or both, the lens can compensate for the deficiency in refractive power. It does this by increasing its convexity, just as the normal eye accommodates for near objects. If this compensatory mechanism suffices, the eye sees distinctly, but since the eye is constantly having to focus for both near and distant objects, instead of only for near objects, like the normal eye, symptoms of eyestrain often result.[5-1, 5-3]

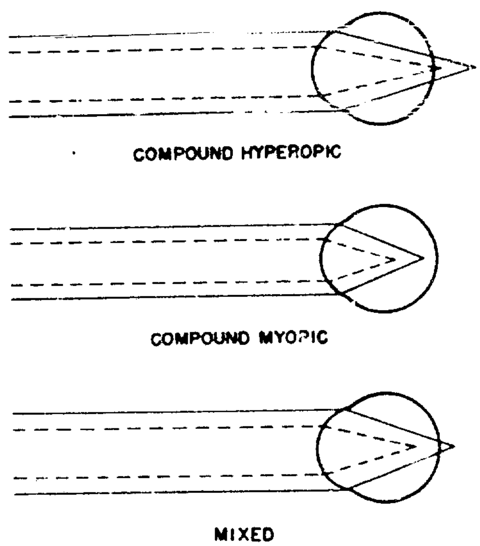


Figure 5.2 Three Types of Astigmatism

If light rays are brought to a focus unequally in relation to the retina, astigmatism exists. Three kinds of astigmatism are illustrated in Figure 5.2. In compound hyperopia, parallel light rays are all brought to a focus behind the retina when the eye is at rest, but they are brought to a focus at different points behind the retina, depending on where they strike the cornea and lens. In compound myopia, the rays are similarly brought to a focus at different points in front of the retina, and in mixed astigmatism, some come to a focus behind and some in front of the retina. Astigmatism causes indistinctness of vision and may cause symptoms of eyestrain. Astigmatism blurs the image unequally due to the fact that resolution is better in some meridians than others.[5-10] It is more likely to cause eyestrain if the axis of astigmatism is at oblique angles.[5-1,5-3]

Presbyopia results from the diminishing ability of the eye lens to increase its convexity to accommodate (focus) for near objects. The ability to increase its convexity diminishes gradually from birth until the age of seventy, when for all practical purposes, all lens elasticity is lost. Therefore, the near point at

which objects can be seen distinctly gradually recedes with age (Fig. 5.3). At about the age of 40-45, it has receded to the point where it handicaps most individuals in seeing close objects, such as fine print. The difficulty is more pronounced under conditions of low illumination, when the dilated pupil permits out-of-focus peripheral rays to blur the retinal image, and after illness and fatigue.

Symptoms due to refractive errors are of two types. The first type consists of those symptoms indicating an impairment of vision which are a blurring or doubling of objects. They occur most frequently with myopia and presbyopia, but are also found in significant amounts of astigmatism.

The second type of symptom consists of indications of eyestrain, such as headache, pain in the eye, and eye watering. While these symptoms do not directly reduce visual acuity, they reduce the accomplishment of visual duties by distracting attention and reducing the use of the eyes. This type of symptom occurs most frequently with hyperopia and astigmatism.

The distribution of refractive errors among the population is shown in Figure 5.4.

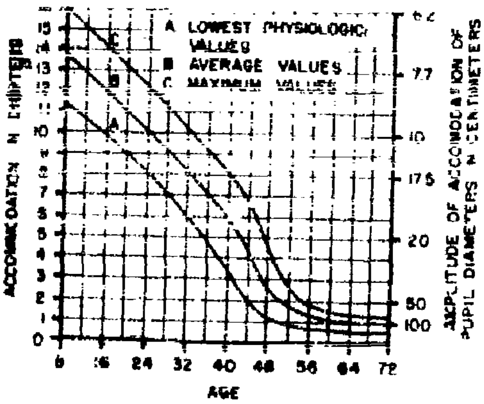


Figure 5.3 Decrease in Accommodation With Age (from Duane[5-9])

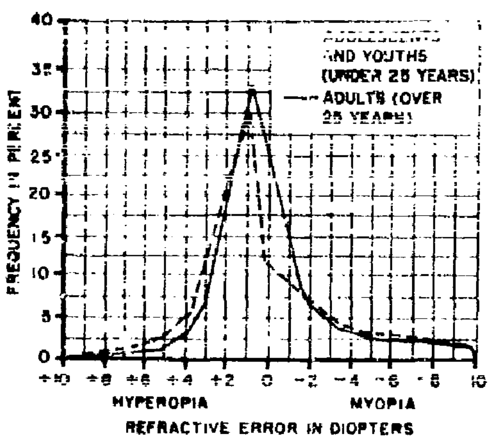


Figure 5.4 Distribution of Refractive Errors among the Population (data from Downing[5-8] Dunstan,[5-11] Gozaley,[5-12] Kronfeld,[5-15] Munson,[5-18] Slataper,[5-20] Tassman,[5-22] and Tron[5-23])

Correction of Refractive Errors

Refractive errors are corrected merely by supplying the type and strength of lens necessary to focus parallel rays of light on the retina.[5-2, 5-10] Thus, for the correction of myopia, a concave lens, called a "minus lens," is supplied to correct the eye's excessive refractive power. A minus lens will shift the focus of parallel rays of light from in front of the retina to the plane of the retina by diverging light rays entering the eye in the amount that the myopic eye produces convergency of light rays.[5-10] Figure 5.5 shows the diverging action of such a lens.

Conversely, a hyperopic eye, which is lacking in refractive power, is made emmetropic by a convex lens, called a "plus lens" (Fig. 5.5), which will converge light rays entering the eye, thus shifting the plane of focus from behind the retina on to the retina.

Astigmatism requires a correcting lens having various planes of focus through it, the nature of the lens power being dependent upon whether the astigmatism is hyperopic, myopic, or a mixture of the two. Such a lens is called a cylindrical lens. Figure 5.5 shows a cylindrical lens, used to correct one type of astigmatism (see Fig. 5.5).

Visual Acuity as an Index to Refractive Errors

Associated with most refractive errors is a deviation from normal vision. Deviation from the normal resolution of objects is measured in terms of visual acuity, the ability of the eye to resolve detail. While there are a number of ways of measuring and expressing visual acuity, the following method is most commonly used in evaluating refractive errors in an individual: First his minimum separable acuity is measured; this is the minimum distance two objects can be apart and still be discerned as distinct objects, measured in minutes of angle subtended at the eye by the separation. The individual's minimum separable acuity is then expressed as a fraction of the minimum separable acuity of the normal eye, or is otherwise compared with normal vision. The average human resolving power, under normal conditions, is one minute of angle; if two objects are separated by less than that amount, the normal emmetropic eye will not discern them as two separate objects. Visual acuity charts ("eye charts") are based on minimum separable acuity.*

The visual acuity recorded is usually referred to twenty feet and expressed in the following fractional form:

$$\frac{\text{distance of letter read by individual being tested}}{\text{distance at which letter could be read by individual with normal resolution}}$$

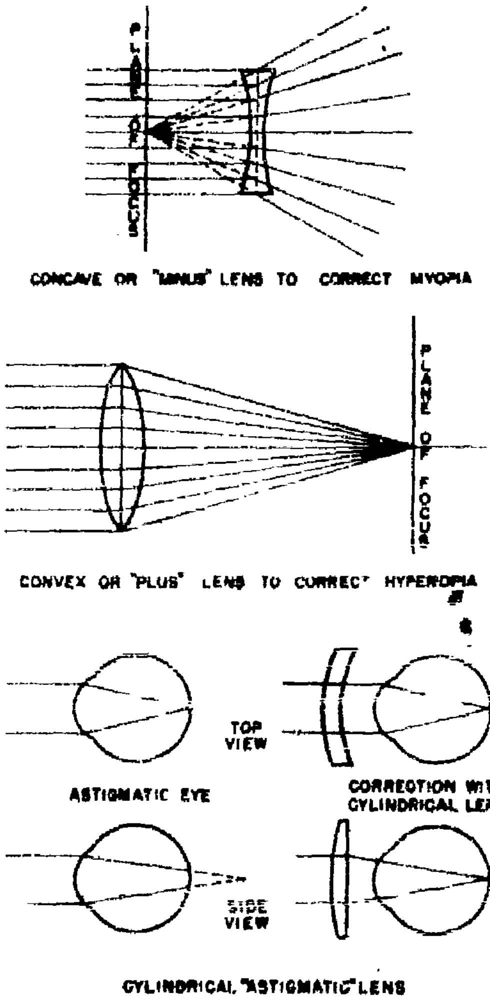


Figure 5.5 Three Types of Lenses Used to Correct Refractive Errors

Thus, 20/40 indicates that the person tested must move to twenty feet to read a letter that can be read at forty feet by an individual having a minimal separable acuity of one minute; 10/200 indicates that an individual tested must move to ten feet to read what could be read by an emmetrope at two hundred feet.

Visual acuity is a partial index to refractive errors, both in amount and type. Almost all myopia, except in negligible amounts, will cause a lowering of the resolving power of the eye. Since in hyperopia,

*Visual acuity is also a function of the brightness, contrast, and other characteristics of the objects viewed and of the state of adaptation, location of the retinal image, and other characteristics of the observer. For a full discussion of this important subject, see Chapter 8.

in the majority of cases, especially younger individuals, the crystalline lens is able to supply the amount of power lacking in the static eye, there is seldom a loss of visual acuity for distant objects unless the amount of hyperopia exceeds or is close to the amplitude of accommodation. Since the accommodation decreases with age, a loss in visual acuity is more likely in the older hyperope than in the younger one with a similar refractive error.

The effect of refractive errors on visual acuity can be best seen by reference to Figure 5.6.

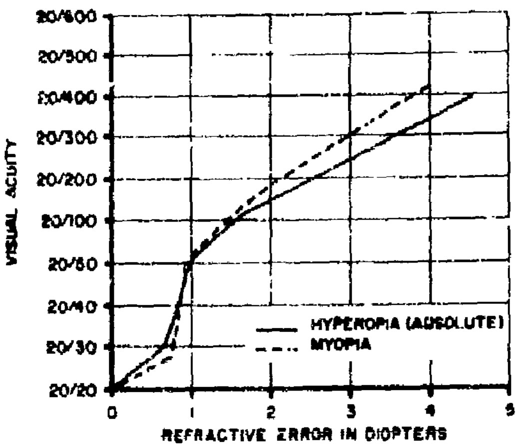


Figure 5.6 Effect of Refractive Errors on Visual Acuity (data from Crawford[5-7] and Pincus[5-19])

Subjective Symptoms Associated with Refractive Errors

Quite often, subjective symptoms accompany refractive errors, mainly in hyperopia, presbyopia, and astigmatism. These symptoms may be divided into two classes, visual fatigue and asthenopia. They are present more frequently when the individual is doing close work. If accommodation of any degree is maintained for an extended period, the individual may note low frontal headaches, lacrimation, smarting, and itching of the eyes, and sometimes actual pain in the eyes. This collection of symptoms is termed asthenopia. There is some difference of opinion regarding the amount of accommodation that can be maintained for extended periods of time without producing asthenopia, but, generally speaking, it is reported to be between two-thirds and one-half the total amount of accommodation. Therefore, it can be seen that the greater the amount of uncorrected hyperopia or presbyopia, the more likely the individual is to experience asthenopic symptoms.

Asthenopic symptoms combined with visual fatigue (a lowering of visual performance) will have the effect of lowering the job performance of the individual. Thus, uncorrected myopes will be able to perform close work longer and more efficiently than the uncorrected hyperope or presbyope. When symptoms are noticed, it is an indication that the individual has reached the point where the mechanism of accommodation can no longer function efficiently at the present working distance. There is some controversy regarding the cause of low frontal headaches accompanying accommodative fatigue. It is generally agreed that they are due to prolonged use of the ciliary body, which controls the action of the crystalline lens, and the squinting required to perceive a clearer retinal image.

Optical characteristics inherent in the corrective lens are often the cause of individual discomfort. The minus, or concave, lens will minify a viewed object, and the effect of a small, bright field will often cause physical discomfort to the corrected myope, especially if he is wearing a first correction or there has been an appreciable change in his prescription. The correction of astigmatism quite often produces a tilted or distorted field of view if a first correction is worn or if the plane of correction is rotated -- especially if it is rotated in a plane oblique to the horizontal plane of the eye. Distance judgment is impaired to some extent, at least initially, until cues, which are sometimes called clues, are relearned. With most corrections, the relearning of visual cues for proper distance judgment requires only a few days, but in some cases of large amounts of oblique astigmatism, the relearning process may be a much larger one, and in some instances the function is never completely regained. When the head is rotated, the eyes lag behind, so that the astigmatic eye is no longer in alignment with the corrective lens. For this reason, astigmatic persons have difficulty in judging distance with their heads tilted.

Progressive Aspects of Refractive Errors

Refractive errors rarely remain constant, and they tend to change over relatively short periods of time. The refractive error most likely to show change is myopia, especially in younger individuals during the years of growth.

Myopia has been classified into three separate types according to its tendency to change. These are stationary, progressive -- which is the more common -- and malignant, in which there is such a rapid change in the refractive error that the condition is considered pathological. The physiological change of the crystalline lens causing presbyopia has already been discussed.

Many studies of refractive changes have been made in private practice and some are presented in Figure 5.7, but additional research is needed.

Corrective Lenses

Corrective lenses for military flying personnel are provided in the following forms: clear spectacle lenses in either a plastic or metal frame, neutral density sun goggles with a 15-percent transmission, and oversized clear goggles with an anti-reflection coating for use in night flying. The use of contact lenses must also be considered in aviation, especially in military aviation.

Spectacle lenses are universally used for ophthalmic correction in the Air Force. They are generally acceptable and perform satisfactorily in most instances for flying personnel. The major disadvantages of spectacles are (1) they cause physical discomfort when they are worn for long periods with a headset, (2) because of their bulk they interfere with the use of optical instruments, (3) they tend to fog, (4) they are relatively insecure on the face, especially during parachute drop and under high g-forces, (5) they cause difficulty when worn under the visor of a high altitude suit, (6) they restrict the visual field, (7) they integrate poorly with certain items of personal equipment, such as helmets and oxygen masks, and (8) when their lenses are of certain refractive powers, they cause aberration and distortion, which result in visual and ocular discomfort.

When Corrective Device Should Be Worn. If the refractive error is such as to degrade visual acuity below 20/20 for distance, or if there are symptoms of eyestrain, a crew member should wear a corrective device while flying. The most difficult near objects to see are instrument faces and the printing on some charts. Low illumination in the cockpit and fatigue add to the difficulty. Cases of presbyopia that are marginal for correction for ordinary reading should be corrected for flying.

Importance of Wearing Spectacles. Air Force Manual 160-1 requires that aircrew members with visual acuity of 20/25 or lower in either eye must wear corrective lenses while flying. The many visual tasks of pilots such as target detection, the reading of a staggering number of panel instruments, the use of optical aids and avoiding of collisions requires that they have clear, comfortable, binocular vision at all times. If the maximum distance for recognition of one type of fighter aircraft is four miles if the pilot possesses 20/15 visual acuity, visual acuity is reduced to 20/20 when the distance is only three miles; a further reduction in visual acuity to 20/30 will shorten the distance to two miles.

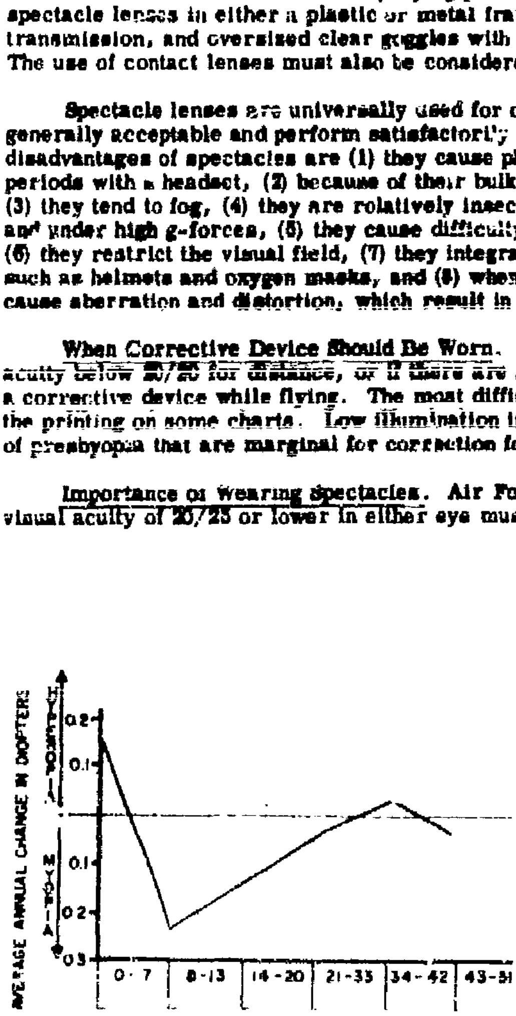


Figure 5.7 Progression of Refractive Errors (data from Brown,[5-4] Bucklers,[5-5] Clark,[5-6] Jackson,[5-13] Kittesy,[5-14] Sourasky[5-21])

Other crew members such as navigators, bombardiers, gunners, and flight engineers whose duties are restricted to the use of instrument dials, optical devices, charts, and radar instruments must have adequate visual acuity for near objects, as well as for distant objects for extended periods of time.

Importance of Vertex Distance. If an ophthalmic lens is prescribed to correct a refractive error, it will do so only when the posterior surface is at the same distance that the test lenses were placed when the eyes were refracted. This distance, the distance of the posterior surface of the lens from the anterior surface of the cornea, is called vertex distance. It is usually about 14 millimeters.

The effective strength of a convex lens is increased by increasing the vertex distance; that of a concave lens is increased by decreasing the vertex distance.

If the vertex distance is changed appreciably, especially when refractive errors are high, the retinal image will not be clear for the individual and there will be a lowering of visual acuity.

It is therefore imperative that spectacles worn by flying personnel be properly fitted to the face of the individual and maintained in that position. If the corrective lens should be placed somewhere other than on the face of the individual, such as in a visor or in an optical instrument, the amount of correction must be altered to correspond with the distance the lenses are moved.

The majority of lenses today are ground in a meniscus form. That is, one surface is concave and the other convex, with the concave surface toward the eye. It was found that if the ocular surface were ground with a radius of approximately 87 millimeters, the visual axis would remain perpendicular to the lens surface during the rotary movements of the eye. The surface is therefore ground to that radius wherever practical; however, in some prescriptions where the refractive errors of the two eyes differ considerably or a concave curvature of 87 mm. would produce a poor cosmetic lens, the radii of curvature of the concave surfaces are matched within limits and ground with radii of curvature that approximate those desired.

When a change in corrective lenses is deemed necessary, the new lenses should be of the same or nearly the same concave curvature as the former lenses for best patient comfort.

Contact Lenses

Contact lenses, now being used in very limited numbers in the Air Force, find certain applications to which spectacle lenses are not adaptable. The general advantages of contact lenses for aircrew personnel are: no supporting appliance is required, they have a minimal fogging problem, the bulk is negligible, distortion and aberration of lenses are eliminated, they are not easily dislodged from the face, and they are not readily broken.

In certain crew positions in which continuous observation of optical and radar instruments is required, contact lenses offer certain additional advantages, the major one being the lack of an ophthalmic appliance in front of the eye; this advantage is of great importance when the eye relief of the optical instrument is small.

Contact lenses also find uses under certain other conditions. These uses have very little application to the problems of aircrew members, and they are mentioned here mainly so that the discussion of these lenses will be complete. These uses are: to correct for and arrest keratoconus (conically bulging cornea), unilateral and bilateral aphakia (absence of the crystalline lens), and irregular astigmatism, to correct visual defects due to surface opacities of the cornea and due to anisemetropia (great difference in refractive error between the eyes), and in certain other medical applications.

Contact lenses in their present form present two major objections for universal application. The first of these is the limited wearing time. Before contact lenses can be widely used in aviation, personnel must be able to wear them for a length of time approaching that for spectacle lenses. Two researchers,[5-17] in their evaluation study, considered the best of the contact lenses to be a fluidless, scleral contact lens. The average wearing time was around seven hours in highly motivated individuals. In most individuals the wearing time will be considerably less. The main source of irritation of a contact lens is the foreign body sensation; and, in some cases, lid irritation results.

The second objection is the expense. In terms of both the cost of the lenses and the manhours expended in fitting, the expense is much greater than with spectacle lenses. The average time consumed in the fitting of a pair of Lacrilens contact lenses was eight and one-half hours and required about twelve office visits. This must be compared with about one hour and two office visits required for the fitting of a pair of spectacle lenses.

In the previously mentioned study,[5-17] the average wearing time for all contact lenses tested was approximately four hours, and certain types could not be tolerated at all.

Other disadvantages of contact lenses are: (1) they are more susceptible to scratching, (2) they are expensive to duplicate in both time and money, (3) fewer agencies produce them, (4) they cannot be kept in stock levels, and (5) they offer no solution for presbyopia, especially when multifocal lenses are required.

For most individuals, the disadvantages of present contact lenses far outweigh the advantages of these lenses in comparison with spectacles.

IMPORTANCE OF HETEROPHORIA AND HETEROTROPIA

Since the earliest days of flying there has been a great interest in the effect of heterophoria on the ability to land aircraft. The finding of large amounts of heterophoria on physical examination has led to the exclusion from flying training of about 4 percent to 15 percent of applying personnel. 5-30, 5-34, 5-41 It has also led to the removal (from flying) of trained pilots. There has been a wide difference of opinion about the importance of heterophoria in flying, and the standards that should exist. Present standards in the Air Force are described in the section on visual standards, later in this chapter.

Explanation of Heterophoria

Normally both eyes turn toward the object being viewed, so that the light falls from the object onto the fovea of each eye. (The fovea is the retinal area having the most acute vision and is in the center of the retinal field.)

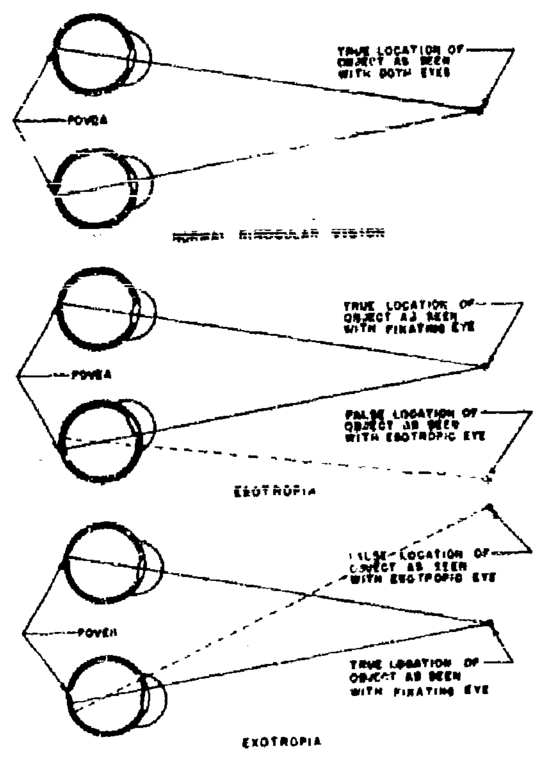


Figure 5.6 Normal Binocular Vision and Heterotropia

In normal binocular vision, eyes are rotated so that image of object in focus falls on fovea of each eye. With heterotropia, image falls on fovea of only one eye, causing doubled image.

If the object is hidden from one eye, that eye may continue to look toward the object. This condition is termed orthophoria, and is present in only a small percentage of individuals. In most individuals when the object is hidden from one eye, that eye turns either in, out, up, or down. These situations are termed respectively esophoria, exophoria, hyperphoria (of the eye from which the object is hidden), or hyperphoria (of the other eye). Collectively they are called heterophorias. Thus, heterophoria exists when the extraocular muscles are so constructed and their enervation is such that the eyes deviate from parallelism when a stimulus for fusion is absent. When the structural deviation from parallelism is too great, or the stimulus to fuse the images from the two eyes is too weak, or both, one eye deviates from the object even when it is not hidden. This condition is termed heterotropia, squint, strabismus, or crossed eyes. This is illustrated in Figure 5.8 In the deviating eye, the light from the object falls on the retina away from its center; therefore, the position of the object as seen by this eye seems to be different from the position as seen by the eye looking directly at the object. This is double vision or "diplopia." Usually, especially in younger individuals, vision is suppressed by the deviating eye after the heterotropia has existed for some months, and so double vision ceases.

Reason for Interest in Heterophoria in Flying

Heterophorias are of interest in flying for four reasons. First, they may cause so-called eye fatigue, headaches, or other symptoms that are likely to interfere with the most efficient performance of flying duties. Second, the heterophoria may progress to a transient heterotropia when the individual is subject to stress in the air, from such things as hypoxia, anxiety, fatigue, or high g-forces. The result here will be double vision. Third, the heterophoria may develop into a more or less permanent heterotropia, perhaps causally unrelated to flying. This first results in double vision, and then usually in suppression of vision in one eye; both of these symptoms are ordinarily incompatible with a continuation of flying. Fourth, heterophoria may impair distance judgment in landing operations.

Therefore, individuals with large amounts of heterophoria are excluded from flying training because of the likelihood of one or more of the above events occurring. After personnel are already trained, indications for removal from flying depend less on the amount of heterophoria than on whether symptoms have developed. These now should be considered in the light of the decrease in eyestrain, headaches, etc. -- the question is, does the annoyance from these symptoms reduce the over-all flying performance to an unsatisfactory level? If the symptoms are in the second category -- transient double vision while under flying stress -- the only decrease in flying performance that can result is from the double vision. If double vision occurs only rarely, it is not likely to be hazardous, provided the individual understands that he must promptly remove the double vision by closing one eye. Of course the question arises as to whether an individual so indoctrinated, who is having repeated attacks of diplopia in the air, will inform the flight surgeon of them. However, experience indicates that he is not likely to conceal anything so alarming to him. In the third category, where the diplopia is of more than rare occurrence, under some conditions of flying stress, the individual can hope to continue flying only if his heterotropia can be corrected by surgery. In the fourth category, the symptom is a decrement in landing performance. The decision here should be based on landing performance and on the likelihood of the heterophoria's getting worse.

Effect of Heterophoria on Landing

This fourth aspect of heterophoria, its effect on landing performance, has been the chief reason for setting standards on heterophoria for flying personnel and for rejecting or grounding because of heterophoria. Because there has been the widest variation of opinion on the effect of heterophoria on landing, a more detailed discussion of this aspect of heterophoria is given in the following paragraphs. Since heterophoria ordinarily does not change greatly in an individual over the years, the important problem is the effect of a static heterophoria on landing. It will be discussed first from the theoretical standpoint and then from the standpoint of the experience of individuals who have flown with large amounts of heterophoria.

Theoretical Considerations

The reasoning for putting a limit on the amount of heterophoria that can be permitted has been as follows: high heterophoria is associated with poor fusion, poor fusion results in poor stereopsis,

and poor stereopsis, results in poor distance judgment in landing aircraft.* This logic breaks down in two places:

First, a high heterophoria is not associated with poor fusion. In fact, in those heterophorias that have never progressed to heterotropia, just the reverse could be expected; that is, the fact that there is a high heterophoria demonstrates that fusion is good enough for the eyes to overcome a large structural deviation (though it is true that a high heterophoria is more likely to progress to a heterotropia, because of the large deviation). A more accurate measure of the fusional ability is the latent deviation plus the deviation in the opposite direction that can be produced by a prism vergence test. Therefore, the finding of high heterophoria alone does not indicate poor fusion.

The second place in which the logic breaks down is in the relation of stereopsis to ability to land aircraft. Poor stereopsis does not always result in poor distance judgment in landing aircraft, at least on prepared runways. As pointed out in Chapter 8, in the section on Distance Judgment, stereopsis is only one of many cues used. It is not helpful beyond a certain distance; in fact, over the nose of the aircraft the distance from pilot to ground is too great for effective stereoscopic vision until the beginning of flareout, and by this time other cues may be more efficient.

Experience

In numerous studies of the relation of heterophoria to success in landing aircraft, very little positive correlation has been found between the two. One study[5-25] has shown that stereopsis is used in forced landings, but not in normal landings on prepared runways. However, the importance of heterophoria even here is doubtful, because other studies[5-28, 5-32] have shown that there is little or no relationship between heterophoria and stereopsis. Some of the early studies were considered to show a definite relationship between heterophoria and the ability to land aircraft, but the controls in these studies were poor or lacking. More recently it was shown[5-44, 5-45, 5-47] that there was no relation between heterophoria and progress in learning to fly. Also, little correlation has been found between performance in the Howard-Dolman distance judgment test and landing ability.[5-26] In two studies, there was no correlation between the heterophorias at distance and landing success.[5-44, 5-45] However, excessive convergence for near objects, or hyperphoria for near objects, did appear in a slightly larger percentage of those who failed in flying.[5-27] These ocular findings could have affected the performance of cockpit duties, and this, rather than landing distance judgment, could have accounted for the difference in flying success -- if the difference was significant. High correlation has been found between basic visual acuity and acuity of stereopsis.[5-36] However, if the personnel have good basic acuity, which is a well established visual requirement, there ordinarily need be little concern for stereoscopic acuity.

Effect of Flying Stresses on Heterophoria

Hypoxia has been found to have a definite effect in changing heterophorias,[5-24, 5-37, 5-38, 5-39, 5-43, 5-46, 5-48, 5-49, 5-50] so has hypoxia plus fatigue.[5-29, 5-31, 5-42] The effect is to increase exophoria and to decrease esophoria. However, hypoxia has been found to have no effect on stereopsis.[5-33, 5-35] With the onset of hypoxia, other deficiencies, such as defective judgment, arise that are more serious than heterophoria or heterotropia; thus, the possible effects of hypoxia should not affect heterophoria standards. In the Air Force of one country where the matter was investigated, there apparently was not a single case of trouble due to heterophoria during periods of hypoxia during World War II. It is well known that anxiety, fatigue, and g-forces cause some heterophorias to progress to a heterotropia. These are the three principal causes for the transient diplopia that occasionally occurs during flight. Of these causes, fatigue is more important because the diplopia is of longer duration, so that it includes the landing period. Some pilots have observed diplopia only after a fatiguing flight, and prior to landing; however, it is interesting to note that the cases that have come to attention landed successfully.

Treatment of Heterophoria

In improving heterophoria, orthoptic treatments are of some value in some cases under some conditions. The treatments are difficult and time consuming, and they have to be intensive to be of

*Stereopsis and other factors in distance judgment are discussed in Chapter 8.

any value. In a case that is wavering between heterophoria and a transient heterotropia, the outcome depends more on the amount and kind of heterophoria and the fusional ability than it does on the orthoptic treatments that may be given. This opinion is widely held by those specialists most experienced in giving orthoptic treatments. These considerations rule out the practical value of orthoptic treatments for military aviators except in salvaging a few trained personnel who are having symptoms from their heterophoria, and in whom the circumstances seem to justify the effort. Surgical correction is more certain and less time consuming, and has salvaged some personnel.[5-40]

Conclusions about Heterophoria

Heterophoria test standards are important chiefly in selecting personnel for flying training rather than in determining flying competence of trained personnel. For the latter, the question to be considered is whether the heterophoria is causing an unacceptable eyestrain or diplopia, is progressing to a heterotropia, or is causing a decrement in landing performance. Present heterophoria selection standards appear fairly reasonable, but they may be higher than necessary for the highest applicant-selectee ratios, and they are probably higher than necessary for the lower applicant-selectee ratios that have prevailed. The measurement of dissociation in heterophoria is a direct rather than inverse measure of fusional ability, but only to the extent of the dissociation. Prism vergence tests, in the opposite direction, using the dissociated position as a base line, are the tests of total fusional ability. Predictions of the likelihood of eyestrain symptoms or heterotropia should be based on both the dissociated position and on total fusional ability. Further studies of the incidence of eyestrain and heterotropia symptoms, according to dissociated positions and fusional abilities, should [illegible] standards that would permit more accurate selection for flying training.

VISUAL STANDARDS FOR FLYING IN U.S. AIR FORCE[5-61]

In the U.S. Air Force, minimum visual standards have been established for the following classes of personnel:

Class	I	Flying training
	IA	Observer
	II	Personnel in primary control of aircraft in unrestricted capacity and observers whose duties require maximum visual capability
	III	Personnel not in primary control of aircraft (pilots in special category and nonrated personnel such as medical personnel and flight engineers)

As of May, 1957, the standards were as described below.

Minimum Visual Acuity

Class:	I	IA	II	III
		Distance Acuity		
Uncorrected	20/20 each eye	20/50 each eye	20/50 each eye	20/200 each eye
Corrected		20/20 each eye	20/20 each eye	20/20 one eye 20/30 other eye
		Near Acuity		
Uncorrected	20/20 each eye	20/20 each eye	20/50 each eye	No limits
Corrected			20/20 each eye	20/20 one eye 20/30 other eye

Accommodative Power

The near point -- the nearest point at which the individual can see objects distinctly when using maximum accommodation -- must be as close as or closer than that corresponding to the following accommodative power:

Class:	I	IA	II	III
Accommodative Power:	Minimum for age	Mean for age	Minimum for age	(No standard)

Minimum and mean accommodative powers for age, in diopters, are as follows:

Age	Minimum for age	Normal mean for age
17	8.8	11.8
18	8.6	11.6
19	8.4	11.4
20	8.1	11.1
21	7.9	[illegible]
22	7.7	10.7
23	7.5	10.5
24	7.2	10.2
25	6.9	9.9
26	6.7	9.7
27	6.5	9.5
28	6.2	9.2
29	6.0	9.0
30	5.7	8.7
31	5.4	8.4
32	5.1	8.1
33	4.9	7.9
34	4.6	7.6
35	4.3	7.3
36	4.0	7.0
37	3.7	6.7
38	3.4	6.4
39	3.1	6.1

Age	Minimum for age	Normal mean for age
40	2.8	5.8
41	2.4	5.4
42	2.0	5.0
43	1.5	4.5
44	1.0	4.0
45	.6	3.6

Maximum Allowable Refractive Error

	Class I	Class IA, II, III
Total Hyperopia	1.75 diopters in any meridian	(No standards)
Total Myopia	0.25 diopter in any meridian	
Astigmatism	0.75 diopter	

Color Vision

Class I and IA maximum allowable errors:

Failure to read correctly 4 of the 14 test charts of the standard color vision test set or 3 of the 17 test plates of the American Optical Company abridged pseudo-isochromatic plates.

Class II and III

As in Class I and IA unless a score of 60 or better is made using the color threshold tester (grade 1).

Night Vision

Test done only if night vision deficiency is suspected.

Class I, IA, II, and III for rated air crewmen only:

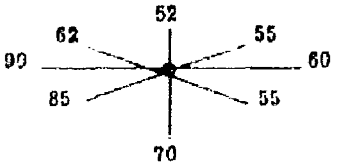
Read Landolt ring in radium-plaque night vision tests, 4 out of 4 or 8 out of 10 types correctly at 5 feet after 30 minutes adaptation.

Field of Vision

Class I and IA

Field for form in any meridian must be to within 15 degrees of the normal mean (see below). Must have no scotoma other than that due to the entry of the optic nerve.

Normal Field for Form (Right Eye)



Class II and III

Same as for I and IA except may have an inactive pathological scotoma if it will not interfere with flying efficiency.

Ocular Movement and Interocular Coordination

Eyes must be movable to normal limits in all meridians. No heterotropia, suppression of vision from one eye, or diplopia permissible. Other maxima for heterophoria and point of convergence are:

Maximum Allowable			
Class:	I & IA	II	III
Esophoria	10 prism diopters	10 prism diopters	No standards
Exophoria	5	5	
Hyperphoria	1	1-1/2	
Point of convergence	70 mm	70 mm	

Depth Perception

No error in group B, C or D using the machine vision tester or no error in eight presentations using the Verhoeff depth perception apparatus. Average error of 30 mm or less using Howard-Dolman apparatus.

Special Requirements for Certain Personnel

Refueling Operator

Visual Acuity (both near and distant): corrected to 20/20

Depth Perception: no errors on machine vision tester or Verhoeff apparatus; average error of 30 mm or less on Howard-Dolman apparatus

Air Traffic Control Operator (Class II) and Radar Operator (not including those on air crew or in air traffic control):

Distance Visual Acuity: corrected to 20/20

Accommodation: near point corresponding to normal mean accommodation for age

Heterophoria: same as for Class I

Night Vision: normal

LIST OF REFERENCES

REFRACTIVE ERRORS

5-1 Anon. Visual Optics. Emsley - Hatton Press Limited.

5-2 Achapousky, S., "Genesis of the Refraction of the Eye." Arch. Ophthal. Vol. 14. 1935. pp. 412-420.

5-3 Borish, I. M., Clinical Refraction. Professional Press, Inc. 1954.

5-4 Brown, D. V. L., "Net Average Yearly Changes in Refraction of Atropinized Eyes from Birth to beyond Middle Life." Arch. Ophthal. Vol. 19. 1938. p. 719.

5-5 Bucklers, M., "Changes in the Refraction during Life." Br. J. Ophthal. Vol. 37. 1953. pp. 587-592.

5-6 Clark, C. V., "Changes in Refraction: From a Study of Case Records during Four Decades." Arch. Ophthal. Vol. 56. 1927. pp. 52-65.

5-7 Crawford, J. S. et al., "Relationship between Visual Acuity and Refractive Errors in Myopia." Amer. J. Ophthal. Vol. 28. pp. 1220-1225.

5-8 Downing, A. H., "Ocular Defects in Sixty Thousand Selectees." Arch. Ophthal. Vol. 33. pp. 137-143.

5-9 Duane, Amer. J. Ophthal. Vol. 5. 1922. p. 865, and Vol. 8. 1925. p. 196.

5-10 Duke-Elder, W. S., Text-Book of Ophthalmology. C. V. Mosby Company, St. Louis, Mo. 1934.

5-11 Dunstan, W. R., "Variation and Refraction." Br. J. Ophthal. Vol. 18. 1934. pp. 404-410.

5-12 Gozaley, A. J., "Frequency of Errors and Refraction." Arch. Ophthal. Vol. 38. p. 698.

5-13 Jackson, E., "Norms of Refraction." Arch. Ophthal. Vol. 6. 1934. p. 704.

5-14 Kittasy, A., "The Stabilization of the Refraction and its Role in the Formation of Ametropia." Br. J. Ophthal. Vol. 33. 1949. pp. 39-47.

5-15 Kronfeld, P. C., and Devney, C., "The Human Refraction Curve." Arch. Ophthal. Vol. 8. 1932. p. 610.

5-16 McCullough, C., "Optical Principles Involved in Correction of Refractive Errors." Arch. Ophthal. Vol. 43. pp. 192-193.

5-17 McGraw, J. L., and Enoch, J. M., "Contact Lenses-Evalvating Study." Trans. Amer. Acad. Ophthal. Vol. 58. July-August 1954. pp. 561-574.

5-18 Munson, E. S., "Emmetrope." Arch. Ophthal. Vol. 29. pp. 109-115.

5-19 Pincus, M. H., "Unaided Visual Acuity Correlated with Refractive Errors." Amer. J. Ophthal. Vol. 29. 1946. pp. 853-858.

5-20 Slataper, F. J., "Age Norms of Refraction and Vision." Arch. Ophthal. Vol. 43. pp. 466-481.

5-21 Sourasky, A., "The Growth of the Eye Development of Myopia: A Study in Changes of Refraction during the School Period." Br. J. Ophthal. Vol. 12. 1938. pp. 625-644.

5-22 Tassman, I. S., "Frequency of the Various Kinds of Refractive Errors." Arch. Ophthal.

5-23 Tron, E., "Statistical Research on Variation in Refraction." Br. J. Ophthal. Vol. 14. 1930. pp. 363-365.

HETEROPHORIA AND HETEROTROPIA

5-24 Anon. BuAir Commerce, U. S. Dept. Commerce, Report 13. May 1938.

5-25 Anon. Visual Factors in Aircrew Selection. Special Study No. 63. The Relationship of the Ocular Findings in the Aircrew Medical Examination to Success in Pilot and Navigator Training. Canada. Royal Canadian Air Force, Director of Medical Services. Great Britain OSRD No. 111-1-2239, N.R.C. Grant No. A.M. 2. February 1, 1945. (CONFIDENTIAL)

5-26 Adamson, G. L., NRC (Canada) No. C-2377. October 1942.

5-27 Anderson, J. R., Trans. Ophthal. Soc., Australia. Vol. 2. 1940. p. 19.

5-28 Ballantyne, A. S., Glasgow Med. J. Vol. 133. 1940. p. 73.

5-29 Berens, C., N. Y. State J. Med. Vol. 40. 1940. p. 1713.

5-30 Crawford, J. S. et al., "Relationship between Visual Acuity and Refractive Errors in Myopia." Amer. J. Ophthal. Vol. 28. pp. 1220-1225.

5-31 Cusick, P. L., Amer. J. Med. Sci. Vol. 204. 1942. p. 306.

5-32 Dudley, W. H., Amer. J. Ophthal. Vol. 2. 1919. p. 119.

5-33 Duguet, J., Med. Aeronaut. Vol. 1. January 1947.

5-34 Duke-Elder, W. S., Text-Book of Ophthalmology. C. V. Mosby Co., St. Louis, Mo. 1934.

5-35 Heinke, E., Luftfahrt Med. Vol. 6. 1942-43. p. 174.

5-36 McCullock, C., and Crush, M., Arch. Ophthal. Vol. 35. 1946. p. 171.

5-37 McFarland, R. A., J. Compar. Physiol. Vol. 23. 1937. p. 227.

5-38 McFarland, R. A., J. Exp. Psychol. Vol. 21. 1937. p. 1.

5-39 McFarland, R. A., Evans, J. N., and Halperin, M. H., Arch. Ophthal. Vol. 26. 1941. p. 886.

5-40 Minnes, J. F., and Shagass, C., Norms Obtained from the Ocular Examination of 2453 Aircrew Candidates. Canada. Royal Canadian Air Force, Director of Medical Services. Great Britain OSRD No. III-I-2237. November 23, 1943. (CONFIDENTIAL)

5-41 Pincus, M. H., "Unaided Visual Acuity Correlated with Refractive Errors." Amer. J. Ophthal. Vol. 29. 1946. pp. 853-858.

5-42 Scobee, R. G., USAF Sch. Avia. Med., Project 292, Report 20. 1944.

5-43 Simpson, R. K., J. Aviat. Med. Vol. 4. 1933. p. 106.

5-44 Tostevin, A. L., Trans. Ophthal. Soc., Australia. Vol. 3. 1941. p. 145.

5-45 Travers, T. B., Trans. Ophthal. Soc., Australia. Vol. 3. 1941. p. 150.

5-46 Weldon, W. H., Ohio State Med. J. Vol. 20. 1924. p. 629.

5-47 Willoughby, L., Trans. Ophthal. Soc., Australia. Vol. 3. 1941. p. 147.

5-48 Wilmer, W. H., Mil. Surgeon. Vol. 52. 1923. p. 1.

5-49 Wilmer, W. H., Arch. Neural. and Psychiatry. Vol. 1. 1919. p. 162.

LIST OF REFERENCES (Cont)

HETEROPHORIA AND HETEROTROPIA (Cont)

5-50 Wilmer, W. H., and Berens, C., J. Amer. Med. Assoc. Vol. 71. 1918. p. 1394.

VISUAL STANDARDS FOR FLYING IN U.S. AIR FORCE

5-51 Anon. Air Force Manual 160-1.

GENERAL BIBLIOGRAPHY

5-52 Anon. Manual of Ocular Tests. A Compilation and Compendium of Ocular Tests Which Are in Use by the Armed Forces of the U.S. of America. The American Optometric Association.

5-53 Anon. Flight Surgeon's Manual. Air Force Manual 160-5.

5-54 Anon. Requirements and Tests for Color Vision: A Summary in Outline Form of Information Which is Pertinent to Color Vision and Test Selection Requirements in the Services. U. S. Naval Submarine Base, Medical Research Laboratory, New London, Conn. May 18, 1944.

5-55 Anon. Standards of Physical Examination for Flying. U. S. Army, Medical Department. Army Regulations No. 40-110, amendment AR 40-110. December 12, 1944.

5-56 Anon. Test of Color Vision. U. S. Army Air Forces. AAF Ltr. 25-29, January 12, 1945, amended by AAF Ltr. 25-334, February 12, 1945.

5-57 Adams, Carlton R., Report of Analysis of Ortho-Rater Scores of Experienced Gunners. U.S. Navy, Bureau of Personnel. February 26, 1945.

5-58 Adams, J. K., Beier, D. C., and Imus, H. A., The Reliability and Precision of the NDRC and Bausch and Lomb Interpupillometers.

5-59 Adams, J. K., Beier, D. C., and Imus, H. A., A Test-Retest Reliability Study of the Bausch and Lomb Orthorater with Naval Personnel. U. S. Ofc. of Scientific Research and Devel., Appl. Psychol. Panel, OSRD No. 3959, U.S. Ofc. of Emergency Management Contract OEMsr-1171, University of Wisconsin, Project N-114, Report No. 6. August 1, 1944.

5-60 Adler, F. H., Clinical Physiology of the Eye. MacMillan Co., New York, N. Y. 1933.

5-61 Adler, Francis H., Physiology of the Eye: Clinical Application. 1953.

5-62 Allphin, W., A Study of Eye Complaints from Fluorescent Lighting. Presented at the Northeastern Regional Conf., Illuminating Engineering Society. June 19-20, 1952.

5-63 Altman, Adelaide, and Rowland, W. M., "Measures of Acuity with Optical Simulation of Distance." Quart. Rev. Ophthal. Vol. 8. March 1952.

5-64 Armstrong, Harry G., Device to Improve Accommodative Errors in Pilots. U. S. Army Air Forces, Materiel Div., Experimental Engineering Sect. May 27, 1940.

5-65 Ashe, W. F., Preselection Tests. U. S. Army Service Forces, Armored Medical Research Laboratory, Project No. 8, Ft. Knox, Ky. April 22, 1944.

5-66 Beals, L. S., and Verplanck, W. S., Further Report on the Testing of Efficiency of Night Vision: Comparative Reliability and Validity Measures on the Adaptometer and the Self-Luminous Tele-Silhouette Adaptometer. U. S. Naval Submarine Base, Medical Research Laboratory, Report No. 14, New London, Conn. January 1943.

5-67 Beebe-Center, J. G., and Mead, L. C., Proposal for a Group Test of Visual Acuity after Dark Adaptation. Tufts Biblio. 35, Commonwealth Fund Report 11, Office of Naval Research, Special Devices Center, Tufts College, Medford, Mass. 1942. pp. 92-106.

5-68 Bennet, Elizabeth A., and Thompson, Dorothy A., "Orthoptic Evaluation of Hyperphoria." Amer. Orthopt. J. Vol. 1. 1951. pp. 13-21.

5-69 Benson, O. O., J. Aviat. Med. Vol. 8. pp. 3, 37.

5-70 Berens, C., J. Aviat. Med. Vol. 3. 1932. p 55.

5-71 Berens, Conrad, and Sells, Saul B., "Experimental Studies on Fatigue of Accommodation. II." Amer. J. Ophthal. Vol. 33. January 1950. pp. 47-57.

5-72 Berens, Conrad, and Sells, Saul B., "Experimental Studies on Fatigue of Accommodation. I. Plan of Research and Observations on Recession of Near Point of Accommodation Following a Period of Interpolated Work on the Ophthalmic Erogograph." Arch. Ophthal. Vol. 31. February 1944. pp. 148-15[illegible].

5-73 Berry, Wm., Miles, Walter, R., and Verplanck, Wm. S., Review of Wartime Studies of Dark Adaptation, Night Vision Tests, and Related Topics. Armed Forces-National Research Council Vision Committee. December 1, 1949.

5-74 Bielschowsky, A., "Functional Disturbances of the Eyes." Arch. Ophthal. Vol. 15. April 1936. pp. 589-603.

5-75 Birren, J. E., Bick, M. W., and Fox, Charlotte, "Age Changes in the Light Threshold of the Dark Adapted Eye." J. Geront. Vol. 3. October 1948. pp 267-271.

5-76 Birren, J. E., and Botwinick, J., "Speed of Response as a Function of Perceptual Difficulty and Age." J. Geront. Vol. 10. 1955. pp. 433-436

5-77 Birren, J. E., Casperson, R. C., and Botwinick, J., "Age Changes in Pupil Size." J. Geront. Vol. 5. 1950. pp. 216-221.

5-78 Birren, J. E., and Shock, N. W., "Age Changes in Rate and Level of Visual Dark Adaptation." J. Appl. Physiol. Vol. 2. 1950. pp. 407-411.

5-79 Blum, Harold F., An Evaluation of Evidence for Injury to the Eye by Sunlight. U. S. Naval Medical Research Institute. June 5, 1944.

5-80 Blum, Harold F., and Fisher, M. B., Measurements of "Visual" Fields with the Perimeter under Conditions of Physiologic Stress. U. S. Naval Medical Research Institute, Project X-149, Report No. 1. November 28, 1945.

5-81 Boice, Marry L., Tinker, Miles A., and Paterson, Donald G., "Color Vision and Age." Amer. J. Psychol. Vol. 61. 1948. pp. 520-523.

5-82 Bouman, H. A., ten Doesschate, J., and DuMarchi Servaas, G. J., "A Modification of Goldmann's Apparatus for the Objective Determination of the Visual Acuity." Opthalmologica. Vol. 122. No. 6. December 1951. pp. 368-374.

5-83 Brailey, A. R., Trans. Ophthal. Soc. United Kingdom. Vol. 39. 1919. p. 42.

5-84 Bray, Charles W., Desirable Characteristics for Adaptometer Tests of Night Vision. Comm. on Human Aspects of Observational Proc. December 13, 1941.

5-85 Brickley, Paul M., and Ogle, Kenneth N., "Residual Accommodation under Homatropine-Cocaine Cycloplegia." Amer. J. Ophthal. Vol. 36. No. 5. May 1953. pp. 649-660.

5-86 Briggs, G. H., Some Physical Aspects of Photoretinitis in Anti-Aircraft Lookouts. Council for Scientific and Industrial Research.National Standards Laboratory, Physics Sect., P.S.S. 7 Australia. February 10, 1943. (CONFIDENTIAL)

5-87 Brown, Kenneth T., "Experiment Demonstrating Instability of Retinal Directional Values." J. Opt. Soc. Amer. Vol. 45. No. 4. April 1955. pp. 301-306.

5-88 Brosek, Josef, "Quantitative Criteria of Oculomotor Performance and Fatigue." J. Appl. Physiol. Vol. 2. 1949. pp. 247-260.

5-89 Brozek, Josef, Somonson, Ernst, and Franklin, Joseph C., "A Note on Methodological Evaluation of Selected Visual Tests." Amer. J. Opthal. Vol. 31. 1948. pp. 979-984.

5-90 Brozek, Josef, Simonson, Ernst, and Keys, Ancel., "A Work Test for Quantitative Study of Visual Performance and Fatigue." J. Appl. Psychol. Vol. 31. 1947. pp. 519-532.

5-91 Byrnes, V. A., Texas State J. Med. Vol. 40. 1944-1945.

5-92 Byrnes, V. A., Scobee, R. G., and Wolpaw, B. J., Manual of Instructions for Clinical Test- [illegible]

5-93 Carleton, Elmer H., and Madigan, Leo F., "Size and Shape of Ocular Images, II. Clinical Significance." Arch. Ophthal. Vol. 7. May 1932. pp. 720-738.

5-94 Carroll, Frank D., and Haig, Charles,"Congenital Stationary Night Blindness without Ophthalmoscopic or other Abnormalities." A.M.A. Arch. Ophthal. Vol. 50. July 1953. pp. 35-44.

5-95 Chapanis, Alphonse, "A Comparative Study of Five Tests of Color Vision." J. Opt. Soc. Amer. Vol. 38. 1948. pp. 626-649.

5-96 Chapanis, A., "The Dark Adaptation of the Color Anomalous Measured with Lights of Different Hues." J. Gen. Physiol. Vol. 30. No. 5. May 29, 1947. pp. 423-437.

5-97 Chapanis, Alphonse, "Diagnosing Types of Color Deficiency by Means of Pseudo Isochromatic Tests." J. Opt. Soc. Amer. Vol. 39. March 1949. pp. 242-249.

5-98 Chapanis, A., The Effect of Refractive Error on Ability to See at Night. U.S. Army Air Forces, Air Tech. Service Command, Engineering Div., Aero Medical Laboratory. 1945.

5-99 Chapanis, A., Night Vision Tests and the Night Vision Testing Program in the Army Air Forces. U. S. Army Air Forces, Materiel Command, Engineering Div., Aero Medical Laboratory. July 20, 1944.

5-100 Chapanis, A., Quantitative Measurement of Visual Fields. Army Air Forces Tech. Report No. 5112, Off. Pub. Bd. Report PB 1421. 1944.

5-101 Chapanis, Alphonse, "Relationship between Age, Visual Acuity and Color Vision." Hum. Biol. Vol. 22. February 1950. pp. 1-35.

5-102 Chapanis, Alphonse, "Simultaneous Chromatic Contrast in Normal and Abnormal Color Vision." Amer. J. Psychol. Vol. 62. 1949. pp. 526-539.

5-103 Chapanis, A., "Spectral Saturation and Its Relation to Color-Vision Defects." J. Exp. Psychol. Vol. 34. 1944. pp. 24-44.

5-104 Chapanis, A., "The Stability of Improvement in Color Vision Due to Training-A Report of Three Cases." Amer. J. Optom. and Arch. Amer. Acad. Optom. Vol. 26. June 1949. pp. 251-259.

5-105 Chapanis, A., and Halsey, Rita M., Photopic Thresholds for Red Light in an Unselected Sample of Color-Deficient Individuals. Contract N5ori-166, T.O. I, Project Desig. NR-507-470, Unpublished Research Report, Office of Naval Research, Systems Coordination Division, Naval Research Lab., and Johns Hopkins University, Psychology Lab. October 1952.

5-106 Chapanis, A., and Pinson, E. A., A Portable Rad[illegible] Plaque Night Vision Tester. TSEAL 3-C-695-37K, U. S. Army Air Forces, Air Technical Service Command, Engineering Div. January 7, 1946.

5-107 Cibis, P. A., and Halperin, M., Faulty Depth Perception Caused by Cyclotorsion of the Eyes. Project 21-24-013, Report No. 1, USAF School of Aviation Medicine, Randolph Field, Texas. September 1951.

5-108 Clements, E. C., Trans. Ophthal. Soc. United Kingdom. Vol. 39. 1919. p. 46.

5-109 Clements, Randolph, Archer, John W., Hays, Ruth, Schoening, Joyce K., Ewing, Paul L., and Emerson, George A., The Effects of Chloroquine on the Speed of Visual Accommodation in Man. Project No. 21-1601-0005, USAF School of Aviation Medicine, in cooperation with Texas University School of Medicine, Randolph [illegible], Texas. [illegible]

5-110 Cook, Ellsworth B., Comparative Performance of Commercial Screening Devices and Far and Near Wall Charts Utilizing the Same Test Targets. Medical Research Lab. Report No. 139, Progress Report No. 5 of BuMed & Surg. Research Project No. NM-003-011 (X-493), U. S. Naval Submarine Base, New London, Conn. August 30, 1948.

5-111 Cook, Ellsworth B., A Factor Analysis of Acuity and Phoria Measurements Obtained with Commercial Screening Devices and by Standard Clinical Methods. Medical Research Lab. Report No. 138, Progress Report No. 4 of BuMed & Surg. Research Project No. NM-003-011(X-493), U. S. Naval Submarine Base, New London, Conn. August 15, 1948.

5-112 Cook, E. B., Visual Acuity Measurement with Three Commercial Screening Devices. Medical Research Lab. Report No. 133, U. S. Naval Submarine Base, New London, Conn. April 22, 1948.

5-113 Counsell, W. D., Trans. Ophthal. Soc. Australia. Vol. 2. 1940. p. 8

5-114 Craik, K. J. W., and Macpherson, S. J., Some Possible Causes of Eyestrain Among Radar Operators. G.B.O.S.R.D. No. WA-1724-23. Great Britain, Psychological Lab., Cambridge University. November 8, 1943.

5-115 Crawford, B. H., and Pirenne, M. H., "Steep Frequency-of-Seeing Curves." J. Physiol. Vol. 126. No. 2. 1954. pp. 404-411.

5-116 Crossland, A. M., A Study of the Ability of Normal and Colour Defective Individuals to Recognize Very Signal Flares and Aldis Lamp Signals. Project V-S-6-3, Royal Canadian Air Force, Rockliffe Air Station, Ottawa, Ontario. October 19, 1942.

5-117 Dashiell, John F., "A Case of Fatigue-Induced Monocular Diplopia." J. Elisha Mitchell Sci. Soc. Vol. 68. 1951.

5-118 De Vries, Hl. "The Fundamental Response Curves of Normal and Abnormal Dichromatic and Trichromatic Eyes." Physica. Vol. 14. August 1948. pp. 367-380.

5-119 Deyo, B. V., Amer. J. Ophthal. Vol. 5. 1922. p. 343.

5-120 Dimmick, Forrest L., and Rudolph, Leon M., Checkerboard Visual Acuity Targets: An Experimental Validation. Medical Research Lab. Report No. 141, Report No. 1 on BuMed Research Project NM 003-008 (X-423), U. S. Naval Submarine Base, New London, Conn. December 15, 1948.

5-121 von, Doesschate, G. T., and Fischer, F. P., Ophthalmologica. Vol. 97. 1939. p. 1.

5-122 Drew, G. C., Variations in Reflex Blink Rate During Visual-Motor Tasks. Great Britain, Flying Personnel Research Committee Report No. 749. December 13, 1950.

5-123 Dunham, Theodore Jr., Binocular Testing Program. Army-Navy-OSRD Vision Committee, Minutes and Proceedings of the Third Meeting. June 16, 1944. pp. 22-31. (CONFIDENTIAL)

5-124 Dvorine, Israel, "Dvorine Color Discrimination Screening Test." Amer. J. Optom. and Arch. Amer. Acad. Optom. Vol. 25. 1948. pp. 130-135.

5-125 Dvorine, Israel, Dvorine Pseudo-Isochromatic Plates. 1953.

5-126 Dvorine, Israel, "Improvement in Color Vision in Twenty Cases." Amer. J. Optom. and Arch. Amer. Acad. Optom. Vol. 23. No. 7. July 1946. pp. 302-321.

5-127 Ellerbrock, V. J., "Experimental Investigation of Cyclofusion." Amer. J. Optom. and Arch. Amer. Acad. Optom. Monograph No. 16. August 1946.

5-128 Elliot, A. J., Report to Director-General of Medical Services, Royal Canadian Air Force. 1949

5-129 Ellson, D. G., and Imus, H. A., Memorandum on the Construction and Calibration of the NDRC Interpupillometer. U. S. Office of Scientific Research and Development, National Defense Research Committee, Appl. Psychology Panel, O.S.R.D. No. 3797, U. S. Office of Emergency Management Contract OEMsr-1171, Project N-114, Memorandum No. 4, University of Wisconsin. June 19, 1944.

5-130 Farnsworth, D., Confusions of Colored Lights at Small Subtense by Protans and Deutans. BuMed X-263 (Av-151-c), Report 108, Medical Research Dept., U. S. Submarine Base, New London, Conn. September 1946.

5-131 Farnsworth, Dean, "Dvorine Color Perception Testing and Training Charts." Science. Vol. 103. 1946. p. 545.

5-132 Farnsworth, Dean, "The Farnsworth-Munsell 100-Hue and Dichotomous Tests for Color Vision." J. Opt. Soc. Amer. Vol. 33. 1943. pp. 568-578.

5-133 Farnsworth, Dean, An Introduction to the Principles of Color Deficiency. Navy Dept. Project NM 003 041.60.01, Report No. 254, BuMed & Surg., Medical Research Lab., U. S. Naval Submarine Base, New London, Conn. September 1954.

5-134 Farnsworth, D., Proposed Armed Forces Color-Vision Test for Screening. U. S. Naval Submarine Base, New London, Conn., Medical Research Lab., Report No. 180. Vol. 10. 1951. pp. 149-155. BuMed Project NM 003 041.10.01.

5-135 Farnsworth, Dean, and Foremen, Priscilla, A Brief History of Lanterns for Testing Color Sensation and Description of the Essential Principles. Report No. 104, Color Vision Report No. 11, Medical Research Lab., U. S. Naval Submarine Base, New London, Conn. April 15, 1946.

5-136 Farnsworth, Dean and Foreman, Priscilla, Development and Trail of New London Navy Lantern as a Selection Test for Serviceable Color Vision. Medical Research Lab. Report No. 105, Color Vision Report No. 12, U. S. Naval Submarine Base, New London, Conn. May 6, 1946.

5-137 Farnsworth, Dean, and Kimple, Priscilla F., Compilation of Research on Abridgment and Administration of the A.O. 1st Edition Pseudo-Isochromatic Plates. Medical Research Lab. Report No. 110, Color Vision Report No. 14, U. S. Naval Submarine Base, New London, Conn. December 9, 1946.

5-138 Farnsworth, D., and Reed, J. D., A Survey of Methods used in Administering Pseudo-Isochromatic Test Plates for Color Vision. Medical Research Lab. Report 30, Color Vision Report No. 3, U. S. Naval Submarine Base, New London, Conn. November 1943.

5-139 Farnsworth, Dean, Reed, J. D., and Shilling, C. W., The Effect of Certain Illuminants on Scores Made on Pseudo-Isochromatic Tests. Medical Research Lab. Report No. 32, Color Vision Report No. 4, U. S. Naval Submarine Base, New London, Conn. November 22, 1943.

5-140 Farnsworth, Dean, Sperling, Harry G., and Kimble, Priscilla F., A Battery of Pass-Fail Tests for Detecting Degree of Color Deficiency. Medical Research Lab. Report No. 147, Vol. 8, 1949. pp. 39-68. Bur. of Medicine Project NM 003-015, U. S. Naval Submarine Base, New London, Conn. August 10, 1949.

5-141 Fisher, M. B., Evaluation of the Data Related to the Revision of the American Optical Company's Pseudo-Isochromatic Plates for Testing Color Vision. Project NMRI-29, U. S. Naval Medical Research Institute. October 21, 1945.

5-142 Fonda, G. E., Green, E. L., and Keagan, F. V., Comparison of Results of Sight-Screener and Clinical Tests. Project 480, Report No. 1, Army Air Force School of Aviation Medicine, 27th Army Air Force Base Unit, Randolph Field, Texas. September 1946.

5-143 Freeman, David M., "Constant Exotropia." Amer. Orthoptic J. Vol. 1. September-October 1951. pp. 22-28.

5-144 Fry, Glenn A., "Monocular Measurement of Visual Acuity Corrected." Optometric Weekly. Vol. 37. 1946.

5-145 Gassovskiĭ, L. N., "Illumination of the Retina of the Non-Observing Eye During Work with Monocular Optical Instruments." Probl. Fiziol. Opt. Vol. 1. 1941. pp. 22-42.

5-146 Giles, G. M., The Distribution of Visual Defects in the Population. From Owen Aves Memorial Lecture delivered to members of Yorkshire Optical Society, Leeds, England. May 18, 1950.

5-147 Ginsburg, B. L., "Rotation of the Eyes During Involuntary Blinking." Nature. Vol. 169. March 1952. pp. 412-413.

5-148 Gordon, D. A., Zagorski, H. J., Woods, I. A., and Reuder, Mary, A Study of Sloan Orthorater Plates as Measures of Visual Acuity at Various Levels of Illumination. Army Project No. 29580100, PJ 3002-08, PRS Report 975, The Dept. of the Army, PR & PBR-Pers Bur-TAGO, Personnel Research Sect. August 1952.

5-149 Gordon, Donald A., Zagorski, Henry J., and Zeidner, Joseph, A Comparison of Ortho-Rater and Wall Chart Visual Acuity Measurements. PRB Research Note No. 10, U. S. Army Adjutant General's Office, Personnel Research Branch. 1953.

5-150 Gordon, D. A., Zeidner, J., Zagorski, H. J., and Uhlaner, J. E., "Visual Acuity Measurements by Wall Charts and Ortho-Rater Tests." J. Appl. Psychol. Vol. 38. No. 1. 1954. pp. 54-58.

5-151 Gore, T. L., and Lawton, W. H., J. Aviat. Med. Vol. 7. p. 172.

5-152 Grant, V. W., J. Exp. Psychol. Vol. 31. 1942. pp. 89-104.

5-153 Grether, Walter F., Connell, Shirley C., and Bjornstad, Jeanne M., Experimental Evaluation of the New London Navy Lantern for Testing Color Perception. Memo. Report MCREXD-694-21B, U. S. Army Air Forces, Materiel Command, Engineering Div., Aero Medical Lab. March 1, 1949.

5-154 Guedry, Frederick E., Jr., Age as a Variable in Post Rotational Phenomena. School of Aviation Medicine and Research Project. NM 001 063.01.19, Joint Project Report No. 19, U. S. Naval Air Station, Pensacola, Fla. November 1, 1950.

5-155 Gulley, Wayne, Leininger, Theodore C., and Wells, J. Gordon, Prescription Spectacles for Flying Personnel. U. S. Air Force School of Aviation Medicine. Randolph Field. Texas. Special Report. November 1952.

5-156 Halsey, Rita M., and Chapanis, A.,"An Experimental Determination of Some Iso-Chromaticity Lines in Color-Deficient Vision." J. Opt. Soc. Amer. Vol. 42. October 1952. pp. 722-739.

5-157 Hansen, A. K., "After-Image Transfer Test in Anomalous Retinal Correspondence." A.M.A. Arch. Ophthal. Vol. 52. September 1954. pp. 369-374.

5-158 Hardy, LeGrand H., Rand, Gertrude, and Rittler, M. Catherine, AO H-R-R Pseudoisochromatic Plates. American Optical Co., 24 plates, Catalog No. 13396, Catalog No. 13396-2. 1955.

5-159 Hardy, LeGrand H., Rand, Gertrude, and Rittler, M. Catherine, "The H-R-R Polychromatic Plates I. A Test for the Detection, Classification, and Estimation of the Degree of Defective Color Vision." A.M.A. Arch. Ophthal. Vol. 51. 1954. pp. 216-228.

5-160 Hardy, LeGrand H., Rand, Gertrude, and Rittler, M. C., "The H-R-R Polychromatic Plates, II. Comparison of Qualitative and Quantitative Classifications by H-R-R and other Tests." A.M.A. Arch. Ophthal. Vol. 52. 1954. pp. 353-367.

5-161 Hargreaves, J. M., Course in Aviation Medicine, George Washington University. 1941.

5-162 Harrington, David O., and Flocks, Milton, "Multiple Pattern Method of Visual Field Examination." J. Amer. Med. Assoc. Vol. 157. February 1955. pp. 645-651.

5-163 Hecht, Selig, The Design and Construction of a Threshold Meter for Measuring the Visual Threshold During Dark Adaptation. Sect. D3, Progress Report No. 1, Contract NDCrc-103, U. S. Office of Scientific Research and Development, National Defense Research Committee, September 22, 1941.

5-164 Hecht, Selig, Means of Improving the Selection, Training, and Employment of Personnel for Military Duties Involving Visual Operations. Management Contract OEMcmr-429, Bimonthly Progress Reports 1-10, U. S. Office of Scientific Research and Development, Committee on Medical Research. U. S. Office of Emergency. April 1, 1944 to October 1, 1945.

5-165 Hendley, C. D., and Hecht, Selig, The Colors of Natural Objects and Terrains and Their Relation to Visual Color Deficiency. U. S. National Research Council, Committee on Aviation Medicine Report No. 269. February 1944.

5-166 Hill, Bradford, and Williams G. O., Statistical Studies of Night Visual Capacity as Measured by the Rotating Hexagon. Great Britain. Flying Personnel Research Committee Report No. 533, OSRD No. II-5-4741. June 1943.

5-167 Hofstetter, H. W., "Some Interrelationships of Age, Refraction, and Rate of Refractive Change." Amer. J. Optom. and Arch. Amer. Acad. Optom. Vol. 31. No. 4. April 1954. pp. 161-169.

5-168 Holmes, William John, "Clinical Applications of Night Vision Tests." Trans. Amer. Ophthal. Soc. Vol. 48. 1951. pp. 422-442.

5-169 Howard, H. J., Amer. J. Ophthal. Vol. 2. 1919. p. 656.

5-170 Hurvich, Leo M., and Jameson, Dorothea, "Some Quantitative Aspects of an Opponent-Colors Theory. II Brightness, Saturation, and Hue in Normal and Dichromatic Vision." J. Opt. Soc. Amer. Vol. 45. No. 8. August 1955.

5-171 Imus, H. A., Project No. X-395, U. S. Naval School of Aviation Medicine, Pensacola, Fla. June 1947.

5-172 Imus, Henry A., The Characteristics of Tritanopia. Tech. Report ONRL-1-52, Office of Naval Research, London. Jan. 11, 1952.

5-173 Imus, H. A., Comparison of Ortho-Rater with Clinical Opthalmic Examinations. Project X-490 (Av-268-p), Report No. 2, U. S. Naval School of Aviation Medicine, Pensacola, Fla. March 1946.

5-174 Imus, Henry A., "Industrial Ophthalmology: Visual Testing Technics." Trans. Amer. Acad. Ophthal. Otolaryng. 1948. pp. 370-384.

5-175 Imus, H. A., and Brogden, W. J., Distributions of Measures of Interpupillary Distance. Appl. Psychology Panel O.S.R.D. No. 1341, U. S. Office of Emergency Management Contract OEMsr-815, Report 1, U. S. Office of Scientific Research and Development National Defense Research Committee, Brown University. March 24, 1943.

5-176 Ishihara, Shinobu, "Tests for Colour-Blindness." (Review) Brit. Med. Bull. Vol. 9. No. 1. 1953.

5-177 Isobe, Kosaku, "Maxwell's Spot and Local Difference of Colour Response in Human Retina." Jap. J. Physiol. Vol. 5. No. 1. March 1955. pp. 9-15.

5-178 Jaeger, Wolfgang, "Question of Genlocalization of Color Vision Deficiencies." von Graefes Arch. Ophthal. (German) Vol. 152. 1952. pp. 385-388.

5-179 Jaeger, Wolfgang, "Are There Combined Forms of Various Types of Color Vision Deficiency? (Protanopia, Deuteranomaly and Tritanomaly in a Family with Two Cases of Non-Allelomorph Compounds)". von Graefes Arch. Ophth. (German) Vol. 151. 1951. pp. 229-248.

5-180 Jaeger, Wolfgang, "Behavior of Protanopes and Deuteranopes at the Short Wave End of the Spectrum." Ber Deutsch. Ophth. Gesellsch. (German) Vol. 56. 1951. pp. 350-352.

5-181 Jaeger, Wolfgang, "Unusual Forms of Manifestation of Congenital Anomalies of Color Vision." Ber. Deutsch. Ophth. Gesellsch. (German) Vol. 56. 1951. pp. 61-65.

5-182 Jaegar, Wolfgang, "Are Congenital Deficiencies in the Red-Green Sense without Exception Inherited Recessively Sex-Linked?" von Graefes Arch. Ophthal. (German) Vol. 152. 1952. pp. 379-384.

5-183 Jaeger, Wolfgang, and Kroker, K., "Behavior of Protanopes and Deuteranopes with Large Stimulation Surfaces." Klin. Monatsbl. Augenh. (German) Vol. 121. 1952. pp. 445-449.

5-184 Jarman, B. L., J. Aviat. Med. Vol. 3. 1932. p. 194.

5-185 Judd, Deane B., "Color Perceptions of Deuteranopic and Protanopic Observers." Journal of Research National Bureau of Standards. National Bureau of Standards, Research Paper RP 1922. Vol. 41. October 1948. pp. 247-271.

5-186 Judd, Deane B., "Standard Response Functions for Protanopic and Deuteranopic Vision." Journal of Research National Bureau of Standards. Vol. 33. December 1944. pp.407-437. Bureau of Standards Research Paper RP1-618. J. Opt. Soc. Amer. Vol. 35. 1945. p. 199.

5-187 Judd, Deane B., Plaza, Lorenzo, and Farnsworth, Dean, "Tritanopia with Abnormally Heavy Ocular Pigmentation." J. Opt. Soc. Amer. Vol. 40. December 1950. pp. 833-841.

5-188 Junker, H., Arch. Fur. Ophthal. Vol. 142. 1940. p. 367.

5-189 Kane, L. A., Correlation of Defective Visual Acuity and Poor Ocular Muscle Balance on Ability to Succeed in Flying Training (E.F.T.S.) Great Britain OSRD No. III-1-2273, C2541, Appendix T. Canada. Royal Canadian Air Force, Director of Medical Services April 1943. (CONFIDENTIAL)

5-190 Kappauf, W. E., and Brogden, W. J., An Instrument for the Measurement of Interpupillary Distance. Applied Psychology Panel, Report No. 2, U. S. Office of Emergency Management Contract OEMsr-815, OSRD No. 1370, U. S. Office of Scientific Research and Development National Defense Research Committee, Brown University. April 5, 1943.

5-191 Kirschberg, L. S. S., Arch. Ophthal. Vol. 36. 1946. p. 155.

5-192 Kirschberg, L. S. S., National Research Council (Canada) No. C-2862. December 1944.

5-193 Koomen, M. J., Scolnik, R., and Tousey, R., "Measurement of Accommodation in Dim Light and in Darkness by Means of the Purkinje Images." J. Opt. Soc. Amer. Vol. 43. January 1953. pp. 27-31.

5-194 Koomen, M., Scolnik, R., and Tousey, R., "A Study of Night Myopia." J. Opt. Soc. Amer. Vol. 41. February 1951. pp. 80-90.

5-195 Krimsky, Emanuel, "An Appraisal of Aviation Eye Tests with Recommendations." J. Aviat. Med. Vol. 25. 1954. pp. 543-552.

5-196 Kumnick, Lillian S., "Pupillary Psychosensory Restitution and Aging." J. Opt. Soc. Amer. Vol. 44. 1954. pp. 735-741.

5-197 Lancaster, W. B., Trans Amer. Ophthal. Soc. Vol. 17. 1919. p. 186.

5-198 Lee, R. H., and Draeger, Rupert H., Design of a Semiautomatic Night Vision Scotometer. Project X-487, Report No. 1, U. S. Naval Medical Research Institute. July 21, 1947.

5-199 LeGrand, Yves, The Existence of Negative Accommodation in Certain Subjects. Comptes rendus des séances de l' Academie des Sciences. (French) Vol. 230. April 12, 1950. pp. 1422-1424.

5-200 LeGrand, Yves, "Sur les Notions de 'Remotum' et d'Accommodation Negative." L'Année Psychologique. (French) Vol. 50. 1951. pp. 179-184.

5-201 Lichtenstein, M., A Study of Visual Skills: Their Distributions and Interrelations. Report 215, Problem 1B1, U. S. Naval Electronics Lab., San Diego, Calif. December 29, 1950.

5-202 Litinskii, G. A., Arch. d'ophthal. Vol. 3. 1939. p. 821.

5-203 Livingston, P. C., The Examination of Night Visual Capacity in Relation to Flying. Great Britain. Flying Personnel Research Committee Report No. 455, Brit. J. Sur. p. 340-345.

5-204 Livingston, P. C., General Results Obtained Among Flying Personnel from Examination of Night Visual Capacity by the Rotating Hexagon. Great Britain. Flying Personnel Research Committee Report No. 438, OSRD Liaison Office Ref. No. WA-574-23b. March 1942.

5-205 Livingston, P. C., Irish J. Med. Soc. Series 6. Vol. 198. 1942. p. 177.

5-206 Ludvigh, Elek, and Kinsey, V. E., "Effect of Long Ultraviolet Radiation on the Human Eye." Science. Vol. 104. September 13, 1946. pp. 246-247.

5-207 McClelland, Dorothy, and Riggs, Lorrin A., Some Uses of the Contact Lens in Research. Tech. Report, Project NR-141-359, Contract N7-onr-358, Task Order II, Brown University. 1950.

5-208 McCord, Fletcher, "Report on the Effect of Training in Color Blindness." J. Clin. Psychol. Vol. 3. No. 2. April 1947. pp. 197-198.

5-209 McFarland, Ross A., Bibliography on the Selection, Training and Physical Fitness of Aviation Pilots. National Research Council Committee on Selection and Training of Civilian Pilots and Civil Aeronautic Authority, Washington, D. C. 1939.

5-210 McGuire, F. L., Kathan, R. H., and Leopold, R. S., Evaluation of Lenses for Correction of Night Myopia. Naval Medical Field Research Lab., Camp Lejeune, N. C.

5-211 McIntyre, A. K., Australia RAAF-FPRC, F.R. 7, 1942.

5-212 McLaughlin, Samuel C., Jr., "An Automatic-Recording Visual Adaptometer." J. Opt. Soc. Amer. Vol. 44. April 1954. pp. 312-314.

5-213 Madigan, Leo F., and Carleton, Elmer H., A Clinical Report of the Corrections of Differences in the Size and Shape of Ocular Images. Annals of the Distinguished Service Foundation of Optometry. 1932. pp. 37-63.

5-214 Mann, Ida, Great Britain OSRD No. WA-2359-2, Great Britain, Ministry of Supply Chemical Board. June 21, 1944.

5-215 Marks, Melvin R., and Uhlaner, J. E., Evaluation of New Armed Forces Vision Tester Plates. PRB Research Report 1092, U. S. Army, Adjutant General's Office, Personnel Research Branch. June 1955.

5-216 Mead, L. C., "The Influence of Size of Test Stimuli, Interpupillary Distance and Age on Stereoscopic Depth Perception." J. Exp. Psychol. Vol. 33. 1943. pp. 148-158.

5-217 Miles, Walter R., and Beaumont, H., "Monocular Testing of the Color-Blind." Amer. J. Ophthal. Vol. 14. No. 7. July 1931. pp. 63?-639.

5-218 Miles, Walter R., and Shriver, Beatrice M., "Aging in Air Force Pilots." J. Geront. Vol. 8. April 1953. pp. 185-190.

5-219 Miller, Earl F., "The Nature and Cause of Impaired Vision in the Amblyopic Eye of a Squinter." Amer. J. Optom. and Arch. of Amer. Acad. Optom. December 1954. pp. 615-623.

5-220 Miller, J. W., and Ludvigh, E., A Shortened Procedure for the Testing of Dynamic Visual Acuity. Contract NOnr-598(00), Office of Naval Research Project Des. No. NR 142-023, Project NM 001 110 501.03., U. S. Naval School of Aviation Medicine, Pensacola, Fla. May 1955.

5-221 Minnes, J. F., Crawford, J. S., and Shagass, C., The Test-Retest Reliability of Ocular Muscle Balance Tests. Medical Selection Board No. 6, Great Britain OSRD No. III-I-2235, Canada, Royal Canadian Air Force, Director of Medical Services. November 23, 1943. (CONFIDENTIAL)

5-222 Morris, A., Katz, Milton S., and Bowen, Jane D., "Refinement of Checkerboard Targets for Measurement of Visual Acuity Limens." J. Opt. Soc. Amer. Vol. 45. 1955. pp. 834-838.

5-223 Mote, F. A., "Variability of Measurements of Human Dark-Adaptation." J. Opt. Soc. Amer. Vol. 45. January 1955. pp. 7-121.

5-224 Mote, F. A., Briggs, G. E., and Michels, K. M., "The Reliability of Measurements of Human Dark Adaptation." J. Exp. Psychol. Vol. 48. 1954. pp. 69-74.

5-225 Motokawa, Koiti, and Isobe, Kosaku, "Spectral Response Curves and Hue Discrimination in Normal and Color-Defective Subjects." J. Opt. Soc. Amer. Vol. 45. No. 2. February [illegible]

5-226 Murray, Elsie, "Mass-Testing of Color Vision: A Simplified and Accelerated Technique." Amer. J. Psychol. Vol. 61. 1948. pp. 370-385.

5-227 Neely, J. C., History of Flying and Heterophoria in England.

5-228 Neely, J. C., Trans. Ophthal. Soc. United Kingdom. Vol. 71. 1951. p. 633.

5-229 Nicholls, J. V. V., Trans. Amer. Ophthal. Soc. Vol. 47. 1949. pp. 650-683.

5-230 Nicholls, J. V.V., Amer. J. Ophthal. Vol. 33. 1950. pp. 1497, 1775, 1891.

5-231 Nicholls, J. V. V., Royal Canadian Air Force Reports. 1941-1944.

5-232 Nicholls, J. V. V., and Minnes, J. F., Orthoptics in Aviation. Great Britain OSRD No. III-I-2230, C2544, Appendix W, Project No. V.S. 903, Canada, Royal Canadian Air Force, Director of Medical Services. December 1942. (CONFIDENTIAL)

5-233 Nickerson, Dorothy, "A Symposium on Color Blindness, Foreward." J. Opt. Soc. Amer. Vol. 33. 1943. pp. 293-294.

5-234 O'Brien, B., A Study of Night Myopia. Tech. Report 53-206, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. May 1953.

5-235 Odland, Lawrence T., and Sloan, Louise I., "Suggested Systems for the Uniform Illumination of Visual Acuity Test Charts." Military Medicine. Vol. 116. No. 1. January 1955. pp. 37-42.

5-236 Ogle, Kenneth N., "Association Between Aniseikonia and Anomalous Binocular Space Perception." Arch. Ophthal. Vol. 30. 1943. pp. 54-74.

5-237 Ogle, K. N., Report on International Nomenclature for Designating Visual Acuity. National Research Council Vision Committee, Ann Arbor, Mich. January 1953.

5-238 Ogle, K. N., J. Opt. Soc. Amer. Vol. 22. 1932. p. 643.

5-239 Ogle, Kenneth N., and Boeder, Paul, "Distortion of Stereoscopic Spatial Localization." J. Opt. Soc. Amer. Vol. 38. 1948. pp. 723-733.

5-240 Ogle, Kenneth N., and Prangen, Avery deH., "Observations on Vertical Divergences and Hyperphorias." A.M.A. Arch. Ophthal. Vol. 49. March 1953. pp. 313-334.

5-241 Pascal, Joseph I., "A Note on True and False Image Projection." Amer. J. Optom. Vol. 31. 1954. pp. 636-639.

5-242 Pascal, J. I., Arch. Ophthal. Vol. 29. 1942. p. 258.

5-243 Peters, George, Jr., "Diagnostic Sensitivity of Color Perception Tests." Optometric Weekly. Vol. 46. 1954. pp. 136-137.

5-244 Peters, George, A. Jr., "The New Dvorine Color Perception Test." Optometric Weekly. Vol. 45. 1954. pp. 1301-1303.

5-245 Pickford, R. W., "The Ishihara Test for Colour Blindness." Nature. Vol. 153. May 27, 1944. pp. 656-57.

5-246 Pickford, R. W., "An Item-Analysis of the Ishihara Test." Brit. J. Psychol. Vol. 41. Parts 1 & 2. September 1950. pp. 52-62.

5-247 Pickford, R. W., "A Pedigree for Three Types of Colour Vision Defect." Nature. Vol. 172. November 28, 1953. p. 1010.

5-248 Pickford, R. W., "Some Problems of Anomalous Colour Vision." Brit. J. Psychol. Vol. 45. 1954. pp. 115-126.

5-249 Pickford, R. W., "A Study of the Ishihara Test for Colour Blindness." Brit. J. Psychol. Vol. 40. 1949. pp. 71-80.

5-250 Pickford, R. W., "Weak and Anomalous Colour Vision in Industry and the Need for Adequate Tests." Occupational Psychology. July 1955. pp. 183-192.

5-251 Pinillos, Jose Luis, "La Piramide Cromatica de Max Pfister (Max Pfister's Color Pyramid Test)." Rev. Psicol. Gen. Apl. Madrid. (Spanish) Vol. 8, 1955, pp. 265-267.

5-252 Prangen, A. deH., "Some Problems and Procedures in Refraction." Arch. Ophthal. Vol. 18. pp. 432-437.

5-253 Rand, G. W., and Ray, James T., Evaluation of the New London Navy Lantern Color Vision Test. Joint Memorandum Report No. 1, School of Aviation Medicine and Research, U. S. Naval Air Station, Pensacola, Fla. May 16, 1950.

5-254 Ripple, P. H., and Sells, S. B., The USAF SAM Ophthalmic Ergograph. Effects of Accommodation-Convergence Exercise. Project 21-24-006, Report 2, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. July 1950.

5-255 Ripple, P. H., and Wilson, M. R., Aniseikonia in Air Force Cadets and its Relationship to the Howard-Dolman Depth Perception Test. Project No. 21-24-010, (Formerly Project No. 21-02-170), U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. August 1950.

5-256 Rose, H. W., A Bright-Adaptation Device for Use with Different Night-Vision Testers. Project 21-31-003, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. April 1952.

5-257 Rose, H. W., and Fleck, Horst, Night Vision Trainer and Training Techniques: I. A Projector for Basic Night Vision Training of Pilots. Project 21-31-010, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. June 1950.

5-258 Rose, S., and Fletcher, J. L., "Response Time as an Indicator of Color Deficiency." J. Appl. Psychol. Vol. 37. 1953. pp. 211-213.

5-259 Rowland, Louise Sloan, Project No. 68, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. July 25, 1942.

5-260 Rowland, Louise S., Daylight Fluorescent Lamps as a Source of Illumination in Tests of Color Perception with Pseudo-Isochromatic Plates. Project No. 130, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. April 1, 1943.

5-261 Rowland, Louise Sloan, Project No. 54, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. May 29, 1942.

5-262 Rowland, Louise Sloan, Further Studies with a Simple Anomaloscope for Detecting Red-Green Color Deficiencies. Project No. 137, Report No. 3, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. September 23, 1943.

5-263 Rowland, Louise S., Selection of a Battery of Color Vision Tests. Project No. 108, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. February 19, 1943.

5-264 Rowland, Louise Sloan, Selection and Validation of Tests for Color Vision - The Color Threshold Lantern as a Quantitative Test for Red-Green Color Deficiency. Project No. 137, Report No. 5, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. October 20, 1943.

5-265 Rowland, Louise Sloan, Selection and Validation of Tests for Color Vision - A Comparison of Two Lantern Tests for Red-Green Deficiency, the Color Threshold Lantern and a Modification of the RCN (Royal Canadian Navy) Lantern. Project No. 137, Report No. 4, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. October 21, 1943.

5-266 Rowland, Louise Sloan, and Rowland, William M., Individual Differences in the Region of Maximal Acuity in Scotopic Vision: Applications to Night Vision Testing and Training. Project 220, Report No. 2, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. February 19, 1945.

5-267 Rowland, William M., Comparison of Howard-Dolman Depth Perception Tests, Wulfeck Group Test of Stereo Acuity, and Keystone Depth Perception Apparatus. Project No. 59, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. July 1, 1942.

5-268 Rowland, William M., and Mandelbaum, Joseph, A Comparison of Night Vision Testers. Project No. 213, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. January 26, 1944.

5-269 Rowland, William M., and Rowland, Louise Sloan, A Comparison of Three Tests of Depth Perception. Project No. 238, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. February 19, 1944.

5-270 Rubin, Leonard S., Medical Lab. Special Report No. 36, U. S. Army Chemical Corps, Army Chemical Center, Md. February 1954. (CONFIDENTIAL)

5-271 Ryan, T. A., Bitterman, M. E., and Cottrell, C. L., "Relation of Critical Fusion Frequency to Fatigue in Reading." Illum. Engng. Vol. 48. 1953. pp. 385-391.

5-272 Sachsenweger, R., Dent. Gesundwes. Vol. 11. No. 26. pp. 883-890.

5-273 Schmidt, Ingeborg, Comparative Evaluation of the Hardy-Rand-Rittler Polychromatic Plates for Testing Color Vision. Project 21-31-013, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. June 1952.

5-274 Schmidt, Ingeborg, Evaluation of the Grether Self-Administering Color Vision Test. Special Report, ASTIA Document 12616, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. March 1953.

5-275 Schmidt, Ingeborg, New Tests for the Examination and Training of Color Vision: Evaluation of the Color Vision Multitester (Signal Lamp) for Aviation. Project 21-29-006, Report No. 4, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. June 1954.

5-276 Schmidt, Ingeborg, "Some Problems Related to Testing Color Vision with the Nagel Anomaloscope." J. Opt. Soc. Amer. Vol. 45. No. 7. July 195.. pp. 514-522.

5-277 Schmidt, Ingeborg, Study of Effect of Illumination on Interpretation of Pseudo-Isochromatic Plates. Special Report, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. May 1951.

5-278 Schwichtenberg, A. H., J. Aviat. Med. Vol. 10. 1939. p. 44.

5-279 Scobee, Richard G., An Analysis of the Ophthalmic Portion of the "64" Examination: (1) Muscle Balance. Project No. 139, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. November 2, 1944.

5-280 Scobee, Richard G., "Anatomic Factors in the Etiology of Heterotropia." Amer. J. Ophthal. Vol. 31. 1948. pp. 781-795.

5-281 Scobee, R. G., A Comparison of Tests for Heterophoria. Project 375, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. April 13, 1945.

5-282 Scobee, Richard G., The Effect of Exhaustion and of Moderate Anoxia on Ocular Muscle Balance. Project No. 292, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. July 18, 1944.

5-283 Scobee, Richard G., "Estropia: Incidence, Etiology, and Results of Therapy." Amer. J. Ophthal. Vol. 34. June 1951. pp. 817-833.

5-284 Scobee, Richard G., "Intermittent Exotropia." Trans. Amer. Acad. Ophthal. Otolaryng. July-August 1949. pp. 658-673.

5-285 Scobee, Richard G., "The Nonsurgical Treatment of Heterotropia." Amer. J. Ophthal. Vol. 32. 1949. pp. 1734-1739.

5-286 Scobee, Richard G., and Bennet, Elizabeth A., "Hyperphoria." Arch. Ophthal. Vol. 43. March 1950. pp. 458-465.

5-287 Scobee, R. G., Berens, C., Cook, E. B. et al., Manual of Instructions for Testing Heterophoria and Prism Divergence at Near. Armed Forces-National Research Council Vision Committee. October 1, 1947.

5-288 Scobee, R. G., and Green, Earl L., A Comparison of Tests for Heterophoria; Reliability of the Screen-Maddox Rod Test. Project 375, Report No. 2, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. July 20, 1945.

5-289 Scobee, Richard G., and Green, Earl L., "Further Studies in the Relationship between Heterophoria and Prism Vergence." Amer. J. Ophthal. Vol. 34. March 1951. pp. 401-404.

5-290 Scobee, Richard G., and Green, Earl L., "Relationships between Lateral Heterophoria Prism Vergence, and the Near Point of Convergence." Amer. J. Ophthal. Vol. 31. 1948. pp. 427-441.

5-291 Scobee, Richard G., and Green, Earl L., "Size of Line in the Maddox-Rod Test." Amer. J. Ophthal. Vol. 31. 1948. pp. 697-699.

5-292 Scobee, R. G., Green, Earl L., and Moss, Herbert L., A Comparison of Tests for Heterophoria; Variations in the Screen-Maddox Rod Test Due to Ocular Dominance, Rod Color, and Screening. Project 375, Report 4, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. July 20, 1945.

5-293 Scobee, R. G., and Moss, H. L., A Comparison of Tests for Heterophoria; Effect of Light and Dark on the Screen-Maddox Rod Test. Project 375, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. July 20, 1945.

5-294 Skeffington, A. M., "Emmetropia." Practical Applied Optometry. Vol. 24. No. 10. October 1952. pp. 87-96.

5-295 ~~Skeffington, A. M., "Hyperopia." Practical Applied Optometry. Vol. 24. No. 11. November~~ 1952. pp. 97-108.

5-296 Sloan, Louise L., and Altman, Adelaide, "Aniseikonia and the Howard-Dolman Test." J. Opt. Soc. Amer. Vol. 43. June 1953. pp. 473-478.

5-297 Sloan, Louise L., and Altman, Adelaide, Evaluation of H.R.R. Plates for Measuring Degree of Red-Green Color Deficiency. Tech. Report, Project N6onr 243-07. 1951.

5-298 Sloan, Louise L., and Habel, Adelaide, "Color Signal Systems for the Red-Green Color Blind. An Experimental Test of the Three-Color Signal System Proposed by Judd." J. Opt. Soc. of Amer. Vol. 45. No. 8. August 1955.

5-299 Sloan, Louise L., and Habel, Adelaide, "Recognition of Red and Green Point Sources by Color-Deficient Observers." J. Opt. Soc. of Amer. Vol. 45. No. 8. August 1955.

5-300 Sloan, Louise L., and Rowland, William M., "Comparison of Ortho-Rater and Sight-Screener Tests of Heterophoria with Standard Clinical Tests." Amer. J. Ophthal. Vol. 34. October 1951. pp. 1363-1376.

5-301 Sloan, Louise, L., Rowland, William M., and Altman, Adelaide, "Comparison of Three Types of Test Target for the Measurement of Visual Acuity." Quart. Rev. Ophthal. Vol. 8. March 1952. pp. 4-16.

5-302 Sorsby, Arnold, "The Nature of Refractive Errors." Brit. Med. Bull. Vol. 9. No. 1. 1953. pp. 22-24.

5-303 Spearman, C., Trans. Ophthal. Soc. U. K. Vol. 39. 1919. p. 36.

5-304 Spencer, Richard W., and Wilson, W. Keith, "Accommodative Response in Asymmetric Convergence." Amer. J. Optom. Vol. 31. 1954. pp. 498-505.

5-305 Stratton, G. M., Psychol. Rev. Vol. 5. 1898. p. 632.

5-306 Sulzman, J. H., Cook, E. B., and Bartlett, N. R., "The Reliability of Visual Acuity Scores Yielded by Three Commercial Devices." J. Appl. Psychol. Vol. 31. June 1947. pp. 236-240.

5-307 Sulzman, John H., Cook, Ellsworth B., and Bartlett, Neil R., Visual Acuity Measurements with Three Commercial Screening Devices. Medical Research Lab. Report No. 93, BuMed & Surg. Research Project No. X-493 (Av-263-p), U. S. Naval Submarine Base, New London, Conn. February 7, 1946.

5-308 Sulzman, John H., Farnsworth, Dean, Cook, Ellsworth B., et al. Comparison of Various Screening Devices with Standard Medical Visual Procedure. Medical Research Lab. Report No. 83, Progress Report No. 1 on BuMed Project No. X-493 (Av-263-p), U. S. Naval Submarine Base, New London, Conn. November 22, 1945.

5-309 Swan, Kenneth C., "The Blindspot Mechanism in Strabismus." Amer. J. Ophthal. Vol. 38. 1954. pp. 765-777.

5-310 Tiffin, J., and Rabideau, G. F., "Reduced Trials and Reliability of Visual-Acuity Thresholds Obtained by the Method of Constant Stimuli. J. Appl. Psychol. Vol. 39. June 1955. pp. 78-81.

5-311 Travis, R. C., Measurement of Accommodation and Convergence Time as Part of a Complex Visual Adjustment. Contract W33-038 ac-14559, TSEAA-694-1H, Report 2, Aero Medical Lab., Engineering Div., Air Materiel Command, Wright-Patterson Air Force Base, Ohio. May 1947.

5-312 Traylen, N. G., Australian Flying Personnel Research Committee Report No. 88, Scientific Liaison Office Reference No. II-5-6276.

5-313 Valentine, J..., Brit. Med. J. Vol. 2. 1923. p. 657.

5-314 Vernon, M. D., Brit. J. Psychol. Vol. 28. 1937. p. 115.

5-315 Verplanck, W. S., Adaptometers for Night Vision Selection and Classification. Army-Navy-OSRD Vision Committee, Minutes and Proceedings of the Third Meeting. June 16, 1944. pp. 32-33. (CONFIDENTIAL)

5-316 Verplanck, W. S., A Rapid Procedure for Testing of Night Vision. Medical Research Lab. Report No. 19, U. S. Naval Submarine Base, New London, Conn. March 5, 1943.

5-317 Verplanck, W. S., A Report on the Night Vision Testing of 5750 Men. Medical Research Lab. Report No. 45, U. S. Naval Submarine Base, New London, Conn. August 12, 1944.

5-318 De Vries, Hl., "The Fundamental Response Curves of Normal and Abnormal Dechromatic and Trichromatic Eyes." Physica. Vol. 14. August 1948. pp. 367-380.

5-319 Wald, George, and Burian, H. M., "The Dissociation of Form Vision and Light Perception in Strabismic Amblyopia." Amer. J. Ophthal. Vol. 27. September 1944. pp. 950-963.

5-320 Walker, R. Y., J. Aviat. Med. Vol. 11. 1940. p. 87.

5-321 Walls, G. L., The Vertebrate Eye and its Adaptive Radiation. Cranbrook Press. Bloomfield Hills. 1942.

5-322 Walls, Gordon L., and Mathews, Ravenna W., New Means of Studying Colour Blindness and Normal Foveal Color Vision: With Some Results and Their Genetical Implications. Also a review by Elsie Murray. Publications in Psychology. Vol. 7. No. 1. University of California. 1952. pp. 1-172. review in Amer. J. Psychol. Vol. 67. No. 1. March 1954. pp. 182-188.

5-323 Weston, H. C., "On Age and Illumination in Relation to Visual Performance." Trans. Illum. Engng. Soc. Vol. 14. No. 9. 1949. pp. 281-297.

5-324 Wheel.. May nard., "Strabismus, Review of the Literature." A. M. A. Arch Ophthal. Vol. 52. 1954. pp. 134-162.

5-325 White, M. S., A Study of the Value of the Pseudo-Isochromatic Color Vision Test in the Selection of the Military Pilot. Project No. 12, Report No. 1, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. January 30, 1942.

5-326 Wilson, Mathew R., Evaluation of the Eye Refractometer. Project 21-0201-0007, U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. ember 1952.

5-327 Wright, W. D.,"Defective Colour Vision." Brit. Med. Bul. Vol. 9. No. 1. 1953. pp. 36-41.

5-328 Zeidner, J., Goldstein, L. G., and Johnson, C. D., Factor Analysis of Visual Acuity Tests during Dark Adaptation. Project 29562000, PRB Tech. Research Note 40, Adjutant General's Office, Personnel Research Branch, Personnel Research and Procedures Div. November 1954.

5-329 Zeidner, J., Gordon, D. A., and Goldstein, L. G., Dark-Adaptation Time for Testing Night-Vision Ability. Project 29562000, Tech. Research Note 25, DA, Personnel Research Branch, Washington, D. C. April 1954.

CHAPTER 6

THE VISUAL FIELD

The ability to see and identify an object depends in part on what part of the retina the image falls. It is therefore important both in visual research and in dealing with practical problems to consider whether the object will be in the center of the visual field (so that the image falls on the fovea) or to what extent it will be away from the center. Charts of the visual field -- the part of space that can be seen without moving head or eyes -- are used for locating objects in terms of degrees from the line of sight (i.e., from foveal vision) and in terms of degrees from a horizontal radius or other reference line.

The monocular field (for one-eyed vision) is limited by (a) the refractive power and physical arrangement of the cornea, lens and retina and (b) the nose, cheeks, and other facial structures. It varies from some 104 degrees from the line of sight on the temporal side (i.e., toward the temples) to some 60 degrees or 70 degrees on the nasal side. The monocular fields of the two eyes overlap to form a binocular field. The visual field can be extended by eye movements, head movements, and body movements.

If an observer fixates a point (i.e., keeps his central vision on it), his ability to discern detail or color, his brightness sensitivity, or some other type of visual performance can be determined as a function of the location of a test object in the visual field. If all the points in the visual field when a given level of visual performance is attained (e.g., the ability just to discern a small detail) are plotted on a chart of the visual field, they form an irregular ring around the center of vision. For most types of performance, lines for decreasingly good performance are found at increasing distances from the center of vision, but the ability to respond to low illumination (i.e., rod vision) increases for some distance toward the periphery.

DEFINITION

The term visual field, as used here, is defined as that part of space that can be seen when the head and eyes are motionless. The visual field in normal two-eyed vision is the binocular field; the field of a single eye is the monocular or uniocular field.

POSITIONS IN THE VISUAL FIELD

When a person is looking directly at a point, he is using his foveal, or central, vision (see Chapter 3). He is said to be fixating the point, and the point may be considered a fixation point. The fixation point lies on the visual axis, or line of sight; this point and any other object on the visual axis appears at the exact center of the visual field. The position of any other point in the visual field can then be given as an angle between the visual axis and a line between that point and the eye. This angle is the eccentricity angle -- the angle by which the point is off-center in the visual field.

The eccentricity angle, then, indicates the distance of any point in the visual field from the center. On charts of the visual field, circles of equal eccentricity are generally drawn about the fixation point as guides (see Fig. 6.1).

For precisely specifying the direction of a point from the center of the visual field, a reference radius is arbitrarily designated as zero degrees. The direction of a point in the visual field can then be given as the angle between the reference radius and a line connecting the point and the center of the visual field. It is customary to provide equally spaced radial reference lines on charts of the visual field (see Fig. 6.1). The line selected as the zero-degrees reference radius varies with different charts.

To locate a point in the visual field, then, we specify its eccentricity and its direction in degrees. For example, point A in Figure 6.1 lies 20 degrees out in the field and 300 degrees from the reference radius. Point B lies 40 degrees out and 150 degrees from the reference radius (or 30 degrees above the horizontal in the upper left quadrant of the field).

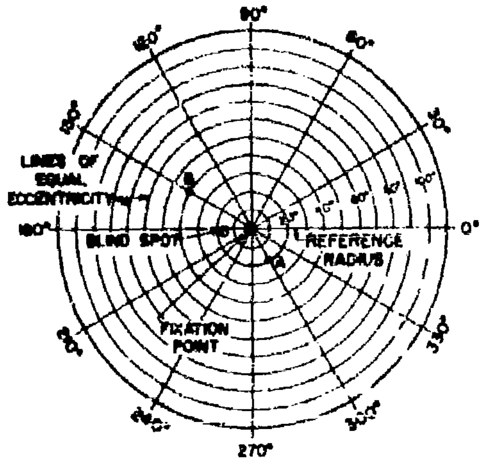


Figure 6.1 Locating Points on a Chart of the Visual Field of the Left Eye

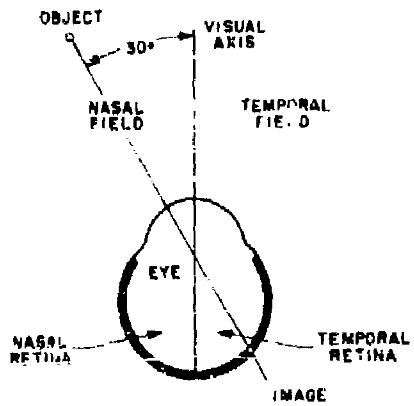


Figure 6.2 Diagram Showing How Object on One Side of Visual Field Produces Image on the Other Side of the Retina (Right Eye is Shown)

The direction from the center of a visual field is also often given as up, down, nasal, or temporal. Nasal refers to the half of the visual field toward the viewer's nose and temporal to the half toward his temple. The terms are limited to a monocular field. Obviously, the nasal half of the field is to the right in the left eye and to the left in the right eye, and the temporal half is to the left in the left eye and to the right in the right eye. Since the field in Figure 6.1 is for a left eye (as shown by the location of the blind spot), point B could be located generally as "40 degrees on the temporal side" or precisely as "40 degrees out and 30 degrees above the horizontal in the upper temporal quadrant."

The terms nasal and temporal are also used to describe positions on the retina of the eye; the temporal retina is the side toward the temple, and the nasal retina is the side toward the nose. Note, however, that an object in the nasal field will be imaged on the temporal retina, and an object in the temporal field will be imaged on the nasal retina, because light rays cross the visual axis. In Figure 6.2, for example, the object lies 30 degrees from the visual axis in the nasal field, but its image is 30 degrees from the visual axis on the temporal retina. Similarly, an object that is up in the visual field will be down on the retina. Therefore, when a direction is specified, the reader should be careful to note whether the author is talking about the object in the visual field or its image on the retina.

VISUAL ANGLE AND OBJECT SIZE

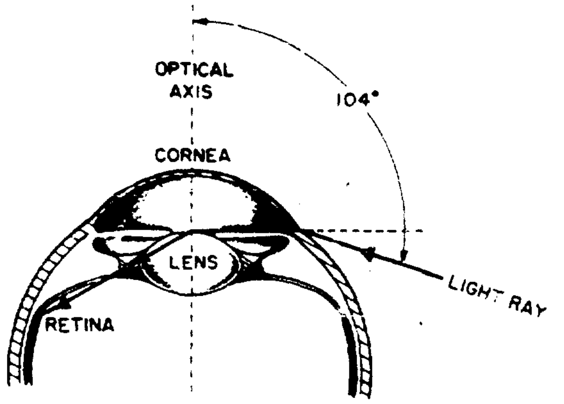
Dimensions of objects, like distances from the visual axis, are often expressed in terms of visual angle -- the angle the object subtends at the eye. Obviously, the farther the object is from the eye, the smaller the visual angle that it subtends; to convert object size into degrees and minutes of visual angle, its distance as well as its size must be known. As an example, an angle of one degree is subtended by an object 0.21 inch long at a distance of a foot; at a distance of one mile, the same angle is subtended by an object 92.4 feet long.

LIMITS OF THE VISUAL FIELD

The visual field is limited by the dimensions of the functional retina, the shape of the cornea and still further by nose, eyebrows, cheek bones, and other structures of the face.

Monocular Field

First, consider the boundaries of the field of a single eye at rest. Because the cornea bulges, light from somewhat "abaft the beam" will strike it. Furthermore, light as much as 104 degrees from the optical axis will be refracted enough by the cornea and lens to strike a sensitive part of the retina (Fig. 6.3). (This angle varies with the location of retinal receptors among individuals.) On a field-of-vision chart, like that in Figure 6.1, this 104-degree limit would appear as a circle of 104 degrees radius, with its center at the fixation point of the eye.



ADAPTED FROM VISION AND THE EYE BY M. H. PIRENNE, BY PERMISSION OF CHAPMAN & HALL LIMITED AND M. H. PIRENNE. 1948. (REDRAWN AFTER H. HARTRIDGE, J. PHYSIOL., 53, XVII, 1919.)

Figure 6.3 How Light 104 Degrees From Optical Axis is Refracted to Strike Retina (after Pirenne6-4, Fig. 17)

However, light cannot reach the eye from an angle of 104 degrees in many directions. The brows cut off light at about 50 degrees in the upper field; the nose forms an irregular barricade at 60 to 70 degrees in the nasal field; and the cheek cuts the lower field at about 80 degrees from the optical axis. In summary, the limits of the monocular field of vision are irregular, and they vary with the facial contours and location of retinal receptors of individuals. The outline of the average monocular field is shown in Figure 6.4.

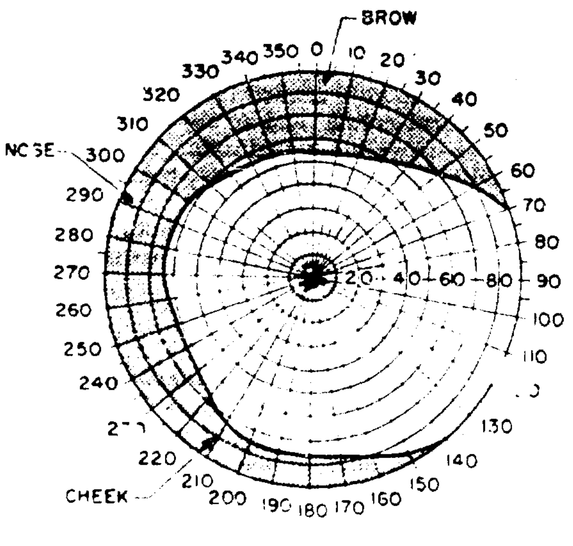
Binocular Field

When both eyes fixate the same point, their visual fields overlap a great deal in the center. This area of overlap -- of true binocular vision -- is shown in Figure 6.5.

Obstructions close to the eye can sharply reduce the area of binocular vision. The loss of visual field must be considered in designing optical equipment and any other equipment that will be located close to the face.

Effect of Eye and Head Movements

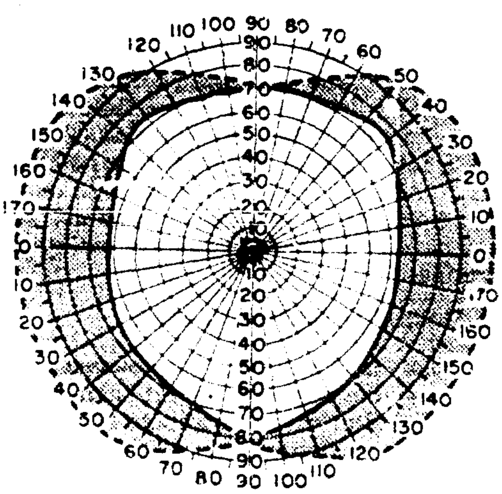
In the foregoing discussion it was assumed that eyes and head were at rest. When the eyes



ADAPTED FROM A TEXT BOOK OF PHYSIOLOGY BY J. F. FULTON. BY PERMISSION OF W. B. SAUNDERS COMPANY AND J. F. FULTON

Figure 6.4 Average Monocular Visual Field (Right Eye) (after Fulton6-2, Fig. 269)

Only on the temporal side does the field extend to the limit set by the eye's refracting powers.



REPRINTED FROM TEXT BOOK OF OPHTHALMOLOGY BY W. S. DUKE-ELDER. BY PERMISSION OF HIRSCHFELD BROTHERS, LIMITED, 1934.

Figure 6.5 Binocular Visual Field (from Duke-Elder6-1, Fig. 931)

The fields of the two eyes overlap in the white area.

are rotated, vision is extended beyond 104 degrees from straight ahead where facial contours do not get in the way. Head and body movements can extend vision through 360 degrees in all planes. For these reasons, we do not usually pay much attention to the limits of our visual field. However, these limits, together with the relative sensitivity of various parts of the retina, are of major importance in aircraft; a pilot must often become aware of another aircraft, a warning signal, or an object on the ground when he is fixating, for example, a target or flight instrument.

Table 6.1 presents data on the average angular limits of the peripheral field of vision and of the range of fixation for five conditions of head and eye movement ranging from maximum movement to none. These values are based on tests with the Ferree-Rand perimeter (perimeters are described in a later paragraph). A white mark subtending one degree of visual angle was used; it was placed on a black background, with 51 foot-candles of illumination.

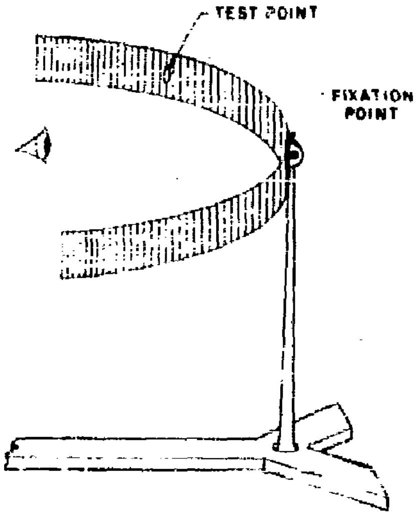


Figure 6.6 A Perimeter

Section (a) of the table, which gives values for easy and natural head and eye movements, is of particular interest. Under these conditions, the total region visible to a two-eyed man encompasses [illegible]0 percent of the surrounding sphere. Moreover, by using maximum head and eye movement -- i.e., without moving his body -- a person can fixate an object seen anywhere in the peripheral field by moderate head and eye movements; in most regions he can fixate the object with both eyes.

LOCATING OBJECTS IN THE VISUAL FIELD FOR TESTS OF VISUAL FUNCTIONS

Visual performance varies with the location of the image on the retina, and hence with the location of the object in the visual field. Therefore, in measuring such visual functions as sensitivity to brightness or ability to detect an object or to judge its shape or size, the light or object being used for the test must be placed a known distance from the visual axis. Usually, a fixation point is provided, and the stimulus is placed a specified number of degrees from it. To test various positions in the field, either the stimulus or the fixation point may be moved.

Sometimes the stimulus is placed on a curved track, the center of curvature being located at the observer's eye. Eccentricity is obtained by moving the stimulus to the desired position on the track, direction by rotating the track to the desired angle. Devices of this sort are called perimeters (Fig. 6.6). Tangent screens are often used for central fields.

When tests of visual performance in various parts of the visual field are made, it is usually found that the ability to perform a certain visual task -- to see a detail of a certain size (visual acuity), to respond to a certain level of brightness, or to identify a color or distinguish between two colors, for example -- decreases (or in some cases increases) with distance from the center of the visual field. If all the points at which a minimum, or threshold, level of performance can be attained are plotted on a chart of the visual field, they thus form a ring, usually rather irregular, around the center of vision. If points are similarly plotted for successively higher levels of performance, the result is a series of roughly concentric rings. For visual acuity, the ability to discern detail, such lines of equal performance are called isopters.

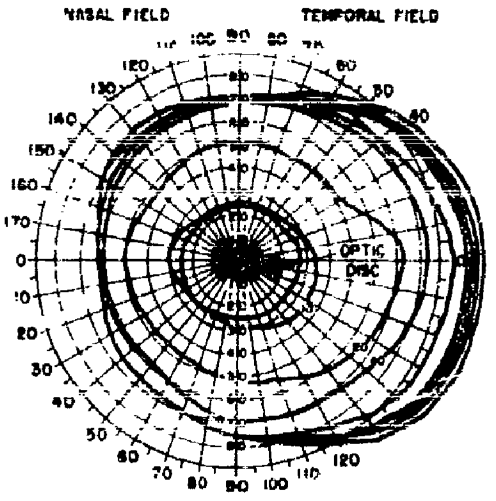
The ability to discern an object in the peripheral field (i.e., outside of foveal vision) is, as would be expected, a function of angle subtended and distance from the line of sight. It is also influenced by (a) the absolute brightness of the object, (b) the brightness contrast of the object with its background, (c) color and color contrast, (d) movement, and (e) the duration of exposure.

It can be seen that charts of isopters can be very useful in solving problems of design and

tactics involving vision. For example, they can help an engineer determine the size, illumination, color, and location of an instrument that must be placed outside the central group of flight instruments; and they can help one predict the distance at which a pilot will see another aircraft coming in from the side while he is looking straight ahead.

Visual Acuity*

Figure 6.7 maps the relative acuity (ability to see detail) for one-eyed daytime vision in various parts of the visual field. The best vision is within a small ring at the very center of the field. Under favorable conditions, thresholds of less than one-half minute of arc have been found in this area. The figures on the larger rings show how many times larger an object must be to be seen clearly at that position than to be seen at the center of the field. It is readily seen that under daylight conditions visual acuity gets rapidly worse as an object progresses in any direction from the center toward the edge of the field. At 6 degrees to 10 degrees out, an object must be about twice as large to be seen as one in the central area; at 20 degrees to 30 degrees out, it must be about ten times as large, etc.



ADAPTED FROM TRAQUAIR'S CLINICAL PERIMETRY [illegible]
BY PERMISSION OF [illegible] LIMITED

Figure 6.7 Monocular Daylight Acuity Relative to Central Acuity (after Duke-Elder[6-1])

Brightness Sensitivity

Different parts of the eye are almost equally sensitive to light at daylight levels of illumination; a light seen out of the corner of the eye will look just as bright as when it is seen with central vision. This is not true, however, at night levels of illumination. At night, the center of the eye (the part used

---

*The following discussion is based on material in Human Factors in the Design of Quartermaster Equipment prepared by Inst. for Appl. Exp. Psychol., Tufts University, for the Office of the Quartermaster General, Sept. 1953.

most in daylight) cannot see very dim lights. But as we go out from the center, the eye becomes more and more sensitive to dim light. In other words, less and less light is required to see an object (see Fig. 6.8). The eye sees best in the zone 10 to 20 degrees from the center of the visual field out in almost any direction. For specifically one-eyed vision, as in the use of some periscopes or telescopes, the portion of this zone lying on the nasal field side of fixation is the most effective, since the temporal field is broken between 11 and 20 degrees by the blind spot. Thus, dim lights are best seen at night by looking slightly to the left of an object with the left eye or to the right of an object with the right eye.

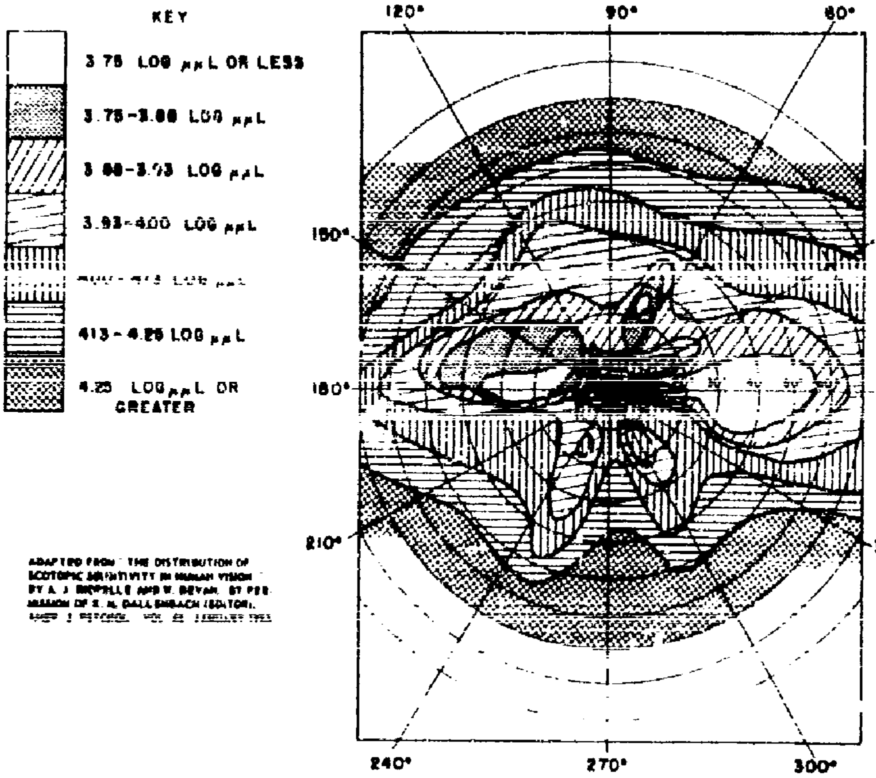


Figure 6.8 A Map of Sensitivity to Light for the Visual Field of the Dark Adapted Right Eye (after Riopelle & Bevan β-5 Fig. 2)

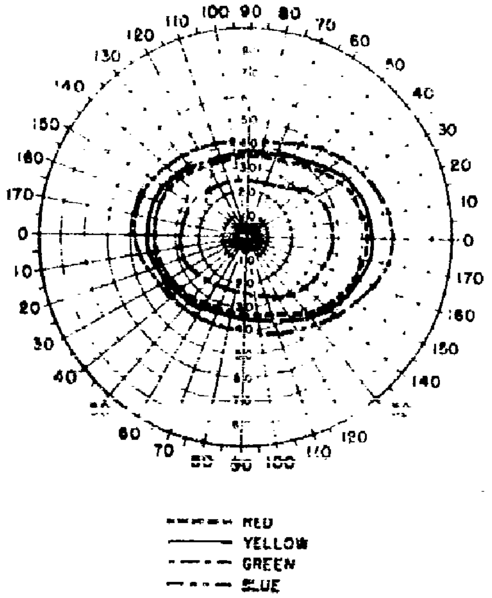
As explained in Chapter 3, this phenomenon is due to the distribution of rods and cones in the retina, the rods, away from the fovea, being more light-sensitive than the cones.

Note that this is one case in which isopters for increasingly good performance occur outward from central vision.

Color Vision

The color of an object varies with its position in the visual field. At moderate levels of illumination, all colors appear as grays at the extreme edges of the field. A little farther in, a blue or

yellow can be recognized, but only at positions near the center of the visual field can a red or green be observed. As you can see in Figure 6.9, there is a fairly restricted region in the center of the field of vision where all colors are seen. Surrounding this zone is a second area in which no red or green is visible as such, but where blue and yellow can be recognized. Even blue and yellow fail toward the extreme edges of the field.



REPRINTED FROM PHILOSOPHICAL TRANSACTIONS BY PERMISSION OF THE ROYAL SOCIETY OF LONDON. ABNEY PHIL. TRAN. CXC. 155. 1897

Figure 6.9 Color Zones for the Right Eye in Moderate Illumination

Outside the ring for a given color, an object reflecting that color will appear gray.

Table 6.1 Horizontal and Vertical Angular Limits of the Human Visual Field

MOVEMENT PERMITTED	TYPE OF FIELD AND FACTORS LIMITING FIELD	HORIZONTAL LIMITS: Temporal Ambinocular Field (each side)	HORIZONTAL LIMITS: Nasal Binocular Field (each side)	VERTICAL LIMITS: Field Angle Up	VERTICAL LIMITS: Field Angle Down
a. Moderate movements of head and eyes, assumed as	Range of fixation	60		45°	
Eyes: 15° right or left, 15° up or down	Eye deviation (assumed)	15°	15°	15°	15°
	Peripheral field from point of fixation	95°	(45°)	46°	67°
Head: 45° right or left, 30° up or down	Net peripheral field from central fixation	110°	60°***	61°	82°
	Head rotation (assumed)	45°	45°	30°*	30°*
	Total peripheral field (from central body line)	155°	105°	91°	112°**
b. Head fixed. Eyes fixed (central position with respect to head)	Field of peripheral vision (central fixation)	95°	60°	46°	67°
c. Head fixed. Eyes maximum deviation	Limits of eye deviation (= range of fixation)	74°	55°	48°	66°
	Peripheral field (from point of fixation)	91°	Approx (5°)	18°	16°
	Total peripheral field (from central head line)	165°	60°***	56°	82°
d. Head maximum movement. Eyes fixed (central with respect to head)	Limits of head motion (= range of fixation)	72°	72°	80°*	90°*
	Peripheral field (from point of fixation)	95°	60°	46°	67°
	Total peripheral field (from central body line)	167°	132°	126°	157°**
e. Maximum movements of head and eyes	Limits of head motion	72°	72°	80°*	90°*
	Maximum eye deviation	74°	55°	48°	66°
	Range of fixation (from central body line)	146°	127°	128°	156°**
	Peripheral field (from point of fixation)	91°	Approx (5°)	18°	16°
	Total peripheral field (from central body line)	237°	132°	146°	172°**

*Estimated by the authors on the basis of tests on a single subject

**Ignoring obstruction of body (and knees if seated). This obstruction would probably impose a maximum field of 90° (or less, seated) directly downward; however, this would not apply downward to either side.

***This is the maximum possible peripheral field; rotating the eye in the nasal direction will not extend it, because it is limited by the nose and other facial structures rather than by the optical limits of the eye. The figures in parentheses on the line above are calculated values, chosen to give the maximum limit thus indicated.

NOTES

1 All data except as noted are from Hall and Greenbaum[6-3]

2 The ambinocular field is defined here as the total area that can be seen by either eye; it is not limited to the binocular field, which can be seen by both eyes at once. That is, at the sides, it includes monocular regions visible to the right eye but not to the left, and vice versa.

3 The term binocular is here restricted to the central region that can be seen by both eyes simultaneously (stereoscopic vision). It is bounded by the nasal field-limits of the eyes

LIST OF REFERENCES

6-1 Duke-Elder, W. S., Text-Book of Ophthalmology. The C. V. Mosby Co., St. Louis, Mo. 1934.

6-2 Fulton, J. F. (Editor), A Textbook of Physiology, Seventeenth Edition. W. B. Saunders Co., Philadelphia, Penn. 1955.

6-3 Hall, M. V., and Greenbaum, L. J., Jr., "Area of Vision and Cockpit Visibility." Trans. Amer. Acad. Ophthal. Otolaryng. September-October 1953.

6-4 Pirenne, M. H., Vision and the Eye. Chapman and Hall Limited. 1948.

6-5 Riopelle, A. J., and Bevan, W., Jr., "The Distribution of Scotopic Sensitivity in Human Vision." Amer. J. Psychol. Vol. 66. 1953. pp. 73-80.

GENERAL BIBLIOGRAPHY

6-6 Bender, Morris B., and Krieger, Howard P., "Visual Functions in Perimetrically Blind Fields." A. M. A. Arch. Neurol. and Psychiatry. Vol. 65. January 1951. pp. 72-79.

6-7 Brown, Kenneth T., "Factors Affecting Differences in Apparent Size Between Opposite Halves of a Visual Meridian." J. Opt. Soc. Amer. Vol. 43. June 1953. pp. 464-472.

6-8 Harrington, David O., Textbook and Atlas of Clinical Perimetry. The C. V. Mosby Co. 1956.

6-9 Schwichtenberg, A. H., "The Effect of the Present Type of Goggles on the Normal Field of Binocular Vision." J. Aviat. Med. Vol. 6. 1935. pp. 68-70.

6-10 Sutro, P. J., The Evaluation of Windshield-Window Solid Angles with Respect to Human Visual Fields. Proc. of 33rd Meeting Armed Forces-NRC Vision Committee. November 12-13, 1953.

6-11 Traquair, Clinical Perimetry. London, England. 1931.

CHAPTER 7

PURPOSES AND PRINCIPLES OF PSYCHOPHYSICS

Psychophysical tests involve the measurement of people's responses in terms of the stimuli producing them. As in many types of scientific research, the experimenter usually tries to manipulate only one variable, keeping the others constant. Because of the many variables that can influence a test, a number of judgments of response are usually obtained. The experimenter then gets a range of values, a mean, or the deviation from the mean. By methods derived from common statistical practices, he can determine whether differences are statistically significant -- whether they are due to chance alone or to his manipulating a variable.

Psychophysical methods are used for the following purposes: (1) experimental, to determine how a change in a stimulus affects response; (2) normative, to determine how the vision of an individual varies from normal vision in one or more aspects; (3) measurement of the stimulus, to measure a physical characteristic of an unknown stimulus by comparing it with stimuli whose physical characteristics are known; (4) measurement of sensation, to derive a scale of values for sensation by such a procedure as reporting when a sensation appears to have halved or doubled as physical characteristics of the stimulus are changed.

Since rather simple judgments of sensations are the easiest to compare to a stimulus value, observers are often asked to state when they can first see an object (absolute threshold), when they can first detect a difference between stimuli (differential threshold), or when two stimuli are equal.

Most psychophysical methods are based on four "classical methods": (1) Method of average error -- stimuli are manipulated until observer can state they are equal or make some other positive judgment. Although this is a rapid method, unwanted variables may decrease accuracy more in this method than in others. (2) Method of limits -- stimuli are presented in both increasing and decreasing values; observer reports when he can just see, when he can first not see, or when two stimuli are equal. Errors may be caused by tendency to persist in one judgment, anticipation, habituation, or by tendency to change judgments too soon. (3) Method of constant stimuli -- stimulus values are presented at random; observer judges whether he can see the stimulus or whether it is equal to a standard. This is a reliable method, but rather time-consuming. (4) Method of paired comparison -- stimuli are presented in pairs until observer has judged whether each one is greater or less than every other one. This primarily determines the order of magnitude.

BASIC PRINCIPLES IN PSYCHOPHYSICAL METHODS

In Chapter 2 we brought out that in psychophysical measurements in photometry the unobservable responses of an individual are measured in terms of the stimulus producing them; that is, light transmitted by the stimulus -- usually the intensity or luminance of the source.

Obviously the amount of light is not the only characteristic of the stimulus that affects the response. A person's ability to detect and identify an object may depend on, for example, the object's size, shape, velocity, distance, color, position in the visual field, or any combination of these factors. It is therefore not uncommon for visual performance to be evaluated in such units as miles per hour of the stimulus, or tristimulus colorimetric values, or angle subtended at the eye.

At this point, those not well versed in visual science will want to know how the characteristics of the stimulus are varied to test visual performance, and what is found out by doing this.

That is what we are going to explain in this chapter.

Before we go into detail, we bring up two general points that are basic to visual research.

We will usually manipulate only one variable at a time, keeping the others constant. This is not always easy to do; a great many variables affect visual performance, and it is sometimes hard to keep unwanted ones from creeping in to bias the results of an experiment. Even where great care is used to keep the physical characteristics of the stimulus constant, the experiment may be affected by

the characteristics of the person being tested -- the "subject," as he is called, who may have defective vision or exceptionally good vision, or he may have previous experience in making the judgments required in the test. He may achieve results that would be misleading if considered as applying to normal vision. Memorizing the eye chart is the most barefaced method of applying previous experience, but even an honest subject may be aided by having taken similar tests before, or by having practiced the same type of visual performance in his trade. (We may set out deliberately to find out whether experience improves visual performance of one sort or another. Experience is the variable; other conditions are held constant.)

Because visual performance varies among individuals, a number of subjects are usually tested. Because the performance of one individual varies, each subject is often tested a number of times. Sometimes several hundred individual judgments are obtained in one test. One thus finds himself with a spread of numerical values of some characteristic of the stimulus, related to the spread between the best and worst visual performances among the subjects. He will then usually want to derive from this spread of values a single value or a maximum and minimum that will be best suited to the purposes of the experiment.

The results may be expressed simply as a range from lowest to highest score. The range does not tell much about how the majority of persons will score, but it is useful when the extreme limits of performance are important. Suppose, for example, that pilots are being used as subjects in an experiment to decide how big the numbers should be on an altimeter. (This would be a test of visual acuity -- ability to make out detail.) If all the pilots meet U. S. Air Force vision requirements, and all will have to use the altimeter, the letters will have to be designed so that the one with the worst score can read it. Here, the range -- or at least the low end of the range -- is more important than the average.

Often, though not always, scores in tests form a normal distribution curve whose general shape is like that in Figure 7.1; the scores obtained tend to cluster somewhere near the middle score, while above and below the middle the number of scores falls off in such a way as to form the fairly smooth curve symmetrical on both sides.

The arithmetical mean, which is what the word average means, is the sum of all the scores divided by the number of scores. The median is the score above which 50 percent of the scores fall and below which 50 percent fall. Therefore, the average is greatly affected by deviant scores while the median is not, so that the median will be more realistic than the mean in cases in which one or two abnormally high or low scores would make the average considerably higher or lower than most of the individual scores. The mode is the actual score that occurs most frequently of all the scores. It is influenced too much by chance fluctuations to be of great use.

In the distribution curve shown in Figure 7.1, the mean, median and mode all fall very close together. If the distribution were perfectly normal they would fall at exactly the same place.

Sometimes scores will pile up at one or the other end of a distribution instead of the middle and a skewed distribution results. If the scores pile up at the left end and tail down toward the right, the distribution is positively skewed and the median and mean will separate with the median closer to the left end of the distribution than the mean. If the scores pile up at the right end and tail off toward the left the distribution is negatively skewed and the median falls farther to the right than the mean.

When the distribution is normal and symmetrical the standard deviation (SD) is often used to describe the variability of the scores. It is a difference from the mean, and it is defined as:

$$SD = \sqrt{\frac{\sum E^2}{N}}$$

where

E = deviation of individual score from the mean

N = total number of scores

There are, of course, SD's above and below the mean. On the normal distribution curve 68.26 percent of the total scores fall between the -1SD and +1SD. The SD's thus indicate the range of scores

achieved in about two-thirds of the individual tests. If the scores are spread out, then $\sum x^2$, and hence the SD, will have a high value; this will indicate that many subjects have much higher or lower scores than the mean, and the mean is not a good basis for predicting an individual performance. Sometimes the middle 50 percent of scores is considered. The deviation from the mean to each end of this middle group is less than + and -1SD and it is called probable error (PE). PE = 0.6745 SD on a normal distribution curve.

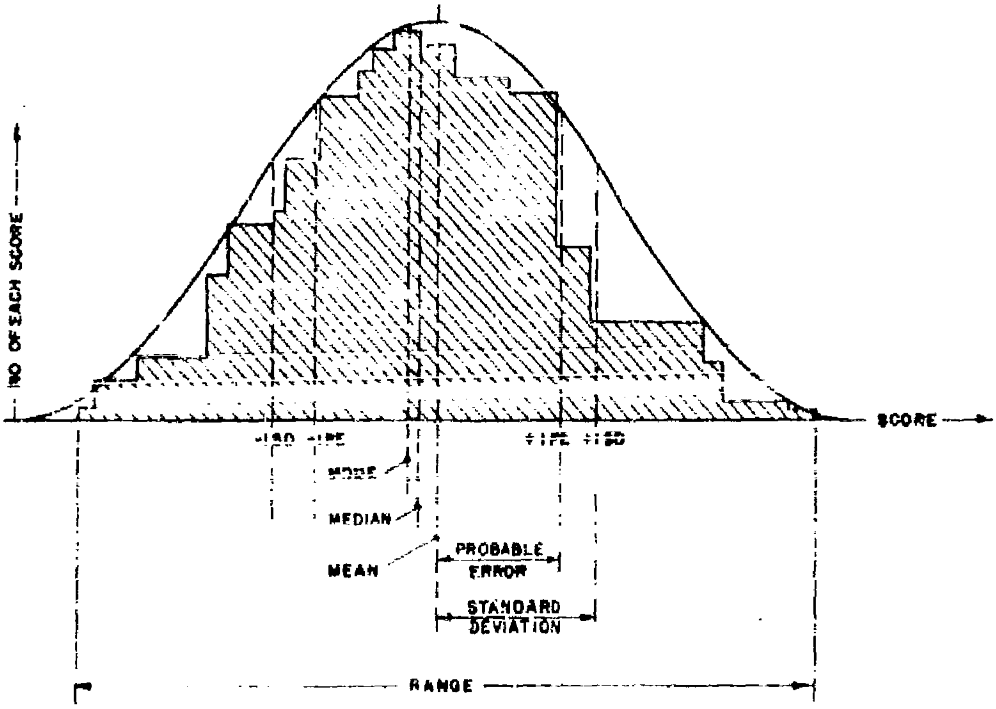


Figure 7.1 Distribution of Scores Approximately Following Normal Distribution Curve

The shaded area represents the actual data; the smoothed curve is obtained mathematically from the data.

Note that the normal distribution curve and the standard deviation and probable error are not theoretical concepts. They are based on an actual distribution pattern of scores that happens to repeat itself in a great many psychological (and biological) tests. They are useful only for results that fit that distribution pattern; for other patterns, they lose their value, although they apply only to tests in which a great many scores are obtained, either through repeated tests of a few individuals or tests of a great many individuals. There are powerful "Small Sample" Statistics available for use.

So far, we have considered only the scores obtained in a test under one set of conditions. If the experimenter now changes a variable and repeats the tests, he may get a different average (or standard deviation, PE, or median). The question now is, is the difference due to chance or is it due to the change in the variable? The answer depends both on the variability of scores within each test and the difference between the two averages. By standard statistical methods (see any textbook on statistics for CR and t-tests), a critical ratio (CR) is obtained. If CR is three or more, the chances are better than 99.865 in 100 that the difference could not be obtained by chance. The difference is therefore statistically significant. For small groups, or where variables other than the one tested cannot be controlled rigidly, more caution must be used in deciding what is statistically significant, and different calculations are often used.

Correlation is important when testing to find out if there is a tie-in between different types of performance. For example, we may want to know if a man able to detect objects under low

"NOTICE: When Government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the U.S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto."

illumination is also likely to be good at recognizing details at long distances. By taking the average scores of the high scorers in a detection test and comparing them with the average score of the same persons in a visual acuity test, a coefficient of correlation is calculated. It may be anywhere from -1.00 to +1.00; a value close to +1.00 means that those who do well in one type of performance will do well in the other. A value close to -1.00 means that the reverse is true; those who do well in one can be expected to do badly in the other. A value close to 0.00 means there is no particular connection between the two types of ability.

PURPOSES OF PSYCHOPHYSICAL TESTS

Now that we have reviewed some of the basic issues in visual testing, let us consider the purposes of visual tests by psychophysical methods.

Experimental

Most of the data we cite in this book was arrived at by psychophysical methods used for experimental purposes. Does a change in a characteristic of the stimulus cause a change in the observer's response? How does it change it? Does a change in radiant energy emitted by a point source cause a change in the sensation of brightness? If it does, how much of a change? Does a change in the color of an airman's life raft make it easier to see against a sea of a given color under average daylight illumination? The question about radiant energy is one of "pure science"; the man asking it is curious about the nature of light and the manner in which the eye responds. The question about the life raft is a very practical one; its answer may save a downed aviator's life. In either case, and in many others, a psychophysical experiment may be set up to help find the answer. All conditions are kept constant except the one to be tested; this one is varied, and the observer reports on his response. He may be asked to report whether he sees the light or object, whether it has changed, or whether it is brighter or in some other way easier to see than a standard stimulus presented for comparison.

In a case like that of the life raft, conditions may be simulated in the laboratory, or a "field test" may be run: life rafts of different colors may be dropped into the sea, and pilots flying toward them may be asked to report which one they see first. Field tests tend to be much rougher than laboratory experiments, but they are useful where conditions are difficult to simulate.

In any case, the experiment may be repeated for the same observer and for different observers until a stable average, standard deviation, or other value is obtained for each condition of the variable. Then, with that variable held constant at the value that gives the best response, or at successive values, similar tests can be conducted by varying a second characteristic of the stimulus. By systematic exploration of all variables, a body of data is built up that may tell a great deal about such basic questions as what causes the eye to respond in a certain way, or about such practical questions as how to design life rafts. The results are expressed in various characteristics of the stimulus -- luminance, visual angle subtended, or whatever is appropriate to the problem at hand. It is not always easy to decide which variable primarily determines the response and which variables are merely "accessories before the fact". In such cases, psychophysics at least provides the data for the combined visual response, and the decision may be reached by the rules of logic or by common sense.

Experimental methods can also be used to test characteristics of the subjects. For example, they may be brought into darkness from a uniformly lighted room and asked to report when they can first see a standard dim light. Dark adaptation time among individuals is now the variable; all other conditions are constant.

Normative

Often the objective is to compare the response of an individual with that of a group of normal observers. In this category are eye tests to find out if a man needs glasses or if he can see well enough to fly. The ability of an individual to respond to a particular stimulus is measured. The results are expressed in units appropriate to the stimulus, but they show how much the individual's capacity varies from the normal. The measurement of visual acuity is an example of such psychophysical techniques. The smallest detail that can be seen under specified conditions is determined by testing a large group of people with "normal vision." In a typical visual acuity test, two objects are moved

apart until the observer announces he can just discriminate between them. Acuity is then expressed in terms of visual angle subtended by the distance between the objects, and the measurement of capacity is expressed as the difference between normal visual acuity and that of the individual. (Visual acuity is explained more fully in Chapter 8.)

Measurement of the Stimulus

Psychophysical techniques can be used to measure a stimulus in a manner analogous to physical measurement. That is, the observer compares an unknown with a standard of measurement in order to find out what magnitude of the standard is equal to the unknown. Measuring with a ruler is a simple example of this procedure. The observer finds the point of equality; he is a null indicator, as it were. In photometry, a spot of light of unknown intensity is compared with a calibrated standard of intensity. When the sensation produced by the unknown is judged equal to that of the standard, the physical measurements of the two are also assumed to be equal. (Usually an average of many judgments is used.) In this manner, the physical characteristics of the stimulus may be measured in physical units by psychophysical techniques.

Measurement of the Sensation

In experimental techniques, described above, the subject's response is usually measured in terms of the characteristics of the stimulus. However, the goal may be to measure the subjective responses (sensations) to stimulation and establish a scale that corresponds to the amount of sensation rather than the physical state of the stimulus. To accomplish this end one must first isolate the stimulus characteristic that is responsible for the response, as in experimental methods. He must then establish the relationship between changes in the stimulus and changes in sensation: that is, he must find a correspondence between a continuum of stimulus values and a continuum of sensation. Having done this, he must devise a scale of sensation values that is based on the relative amounts of sensation reported by the subject and that can be mathematically manipulated. This scale will usually have entirely different proportions from a scale of stimulus values (a small change in stimulus often produces large changes in sensation, and vice versa), but each unit of sensation can be defined in terms of the units on the physical continuum.

In the measurement of visual sensation, some progress has been made toward this goal. For example, we described in Chapter 2 how the sensations of color -- hue, brightness, and saturation -- are expressed in tristimulus values related complexly to the wave length and energy emission of the stimulus. Frequently, scaling of sensations is approached by the method of fractionation: the stimulus value is increased or decreased, and the observer reports when the sensation appears to have halved, doubled, etc., as a result. In working with sensation, one quickly comes to realize that halving or doubling the stimulus does not halve or double the sensation.

Further discussion of the measurement of sensation is beyond the scope of this report. The topic was introduced, however, to allay the notion that psychophysical measurement of the stimulus is the same thing as measurement of the sensation.

THE SUBJECTIVE JUDGMENTS OF PSYCHOPHYSICS

As we have emphasized, psychophysical methods are useful only when objective values can be assigned to the observer's subjective judgments of sensation. Most judgments of sensation are easy to make but hard to pin down. We say with confidence that one red is "twice as bright as another," but others will disagree; the final answer lies in the complex relationships of the two sensations of color to several physical characteristics of both the color samples and the illuminant. Therefore, the researcher often manages his experiments so that his subjects have to make only the simplest kinds of judgments. By manipulating the stimulus values, he can still obtain detailed data that will tell much about complex visual responses. For the purposes of this report, three simple kinds of judgment are especially important.

Absolute Thresholds

Perhaps the easiest judgment for an observer to make is to report whether or not a stimulus is present. Take a stimulus too weak to arouse any sensation at all. As it is increased, a point is reached where the sensation is first detected. This level is called the <u>absolute threshold</u>. Individual

judgments of absolute threshold sometimes vary a great deal. A stimulus of constant physical properties may be detected on one presentation but missed on the next. An absolute threshold must therefore be the average of a number of determinations.

Just Noticeable Difference

An observer may also be expected to detect small differences between stimuli. Two stimuli with exactly the same characteristics are presented. Then a characteristic of one (the comparison stimulus) is changed until the observer reports that he has noticed a change. The point at which a difference is noticed is called the <u>threshold</u>, and the size of the change is called a <u>just noticeable difference</u> (jnd) or <u>differential threshold</u>. The jnd can therefore be expressed in units of the physical stimulus. Jnd units have been used as a basis for building up scales of sensation values, but certain difficulties are encountered. First of all, the change in stimulus required to produce a jnd varies with the initial value of the stimulus. For example, when a light source is dim, a slight change in luminance will be noticed, but when it is bright, a much larger change is required. In other words, when a response increases in what appear to be equal jnd steps, the physical values of the stimulus must increase in unequal steps. It so happens, however, that the sensation sometimes increases in about the same proportion as the log to the base 10 of the stimulus values (i.e., 10 times more stimulus produces twice as much sensation, 100 times the stimulus produces three times as much, etc.). For this reason (and others) graphs of visual performance are often plotted in log units on a linear scale. Unfortunately, the logarithmic relationship between stimulus and response rarely is linear over the entire range of stimulus values. If this fact is kept in mind, the interpretation of visual performance plotted on logarithmic scales should not be misleading.

Equality

The judgment of the equality of two stimuli is a particularly useful one. Its importance in photometry was explained in Chapter 2; other physical characteristics of stimuli, besides the amount of light can be measured in the same way -- by comparison with a standard. In other situations, two stimuli are presented that differ in some physical characteristic. The judgment of equality shows whether the physical difference exceeds the difference threshold for the given sensation. For example, stimulus fields of identical wave length and intensity would be judged equal on the basis of hue. Suppose the intensity of one field were increased while wave length was held constant. Would the hues still be judged equal? For some wave lengths they would; this indicates that the sensation of hue is not determined primarily by the intensity of the stimulus. For other wave lengths, however, they would not; this shows that hue is not purely a function of wave length. It also shows that the parameters of the two stimuli, each of which produces a different sensation, can interact so that a parameter of one stimulus affects the sensation produced primarily by the other stimulus.

CLASSICAL PSYCHOPHYSICAL METHODS

Many psychophysical methods have been developed for presenting stimuli to the observer and for accumulating data on human performance from the observer's judgments. Four more or less basic methods, sometimes called the classical methods, are described below. Most of the other methods are modifications of the classical methods.

The Method of Average Error

When a stimulus can be manipulated easily, either the observer or the experimenter adjusts the stimulus until the required judgment can be made. For example, to determine relative depth discrimination, the relative distance of two vertical rods is adjusted until the observer judges that they are side by side. Usually many adjustments are made. The final value taken is the mean of all the adjustments.

Although this method is probably the quickest way to obtain a good-sized body of data, it is often ruled out because of two disadvantages: (1) The skill and muscular coordination of the observer or experimenter in making the adjustments may affect the observer's performance; his judgments cannot then be taken as depending purely on visual stimuli. (2) The act of making the adjustment may provide extraneous cues that seriously affect the judgments being made. For example, when a stimulus is moved until its size, brightness, or depth is judged equal to that of another stimulus, the relative motion of stimuli may provide a clue. While techniques exist for controlling the extraneous

cues in the apparatus or procedure, they may require so much time that another method would be more efficient.

The Method of Limits

A stimulus is shown to the observer and varied in steps or sometimes continuously through both increasing and decreasing values. Threshold judgments, difference judgments, or equality judgments can be obtained. At some point in the series presentation, the observer will reverse his judgment -- from "present" to "not present," for example, or from "equal" to "not equal." Since observers tend to become "habituated" -- to persist in a judgment after they should reverse it -- stimulus values at the reversal point are averaged for both increasing and decreasing presentations. Nevertheless, habituation may not be the same each way; it remains an undesirable feature of the method of limits, and care must be taken to eliminate its effects by varying the starting points of the series and the size of the step or rate of change used.

The Method of Constant Stimuli

Discrete stimulus values from a series are presented in random order to the observer. To obtain a threshold value, the observer states whether the stimulus can be detected or not. The stimulus value detected 50 percent of the time is then taken as the threshold. To obtain a judgment of equality, the observer states whether the stimulus is greater or less than a standard. The point of equality is the stimulus value at which the judgments of greater or less are split fifty-fifty. This method has none of the disadvantages of the first two methods, and it lends itself well to graphical and statistical solutions. Several variations of this method exist. However, they all probably take more time than the other two methods.

The Method of Paired Comparison

From a group of stimuli, a pair is presented to the observer; he judges which stimulus of the pair is greater in the characteristic being tested. The process is repeated until every stimulus in the group is paired with every other stimulus. This method is best suited to determining the order of magnitude of stimuli, but it can be modified to solve other problems. The collection of data and the analysis required to arrange the stimuli in order of magnitude can be laborious when many stimuli are compared, although short-cut methods exist for handling the data.

OTHER TECHNIQUES FOR PRACTICAL PROBLEMS

Up to this point, we have discussed methods for determining the finest limits of visual perception and discrimination. Sometimes, however, the investigator is more interested in the over-all efficiency with which a human operator uses visual cues in a practical situation. In this case, he may compare the relative speed or accuracy with which an operator can perform a task under two conditions. For example, a radar operator's speed in detecting a pip may be measured (1) when the pip appears alone and (2) when its appearance is accompanied by an auditory "beep." Or, the investigator may find out what work setup is more efficient for performing a task by simply counting the number of operators required under each setup. A researcher sometimes has the same problems as the efficiency expert in engineering. In tracking down sources of error in a manufacturing process, it is often uneconomical to close down production to perform a controlled experiment; sometimes, in fact, the equipment must be operating normally for errors to be determined.

In applied visual experimentation it is often impossible to attain the ideal of changing only one variable at a time. In such cases, a statistical treatment of data, such as analysis of variance, must be used to determine which factors affect visual performance.

GENERAL BIBLIOGRAPHY

7-1 Anon. Handbook of Human Engineering Data. Tufts Inst. for Appl Exp. Psych., Medford, Mass. 1949. Revised 1951.

7-2 Andrews, T. G., Methods of Psychology. John Wiley and Sons, New York, N. Y. 1948.

7-3 Attneave, Fred, "Psychological Probability as a Function of Experienced Frequency." J. Exp. Psychol. Vol. 46. No. 2. August 1953. pp. 81-86.

7-4 Arnoult, M. D., Gagne, R. M., and Vanderplas, J. M., A Comparison of Four Measures of Visual Discrimination of Shapes. Project No. 21-09-001. Research Bull. 51-23. HRRC, Air Training Command, Lackland Air Force Base, San Antonio, Texas. October 1951.

7-5 Bartley, S. Howard, The Psychophysiology of Vision. 1951.

7-6 Blackwell, H. Richard, Psychophysical Thresholds: Experimental Studies of Methods of Measurement. Engng. Research Bull. No. 36. University of Mich. Press. January 1953.

7-7 Blackwell, H. Richard, "Studies of the Form of Visual Threshold Data." J. Opt. Soc. Amer. Vol. 43. June 1953. pp. 456-463.

7-8 Blackwell, H. Richard, "Studies of Psychophysical Methods for Measuring Visual Thresholds." J. Opt. Soc. Amer. Vol. [illegible] September 1952. pp. [illegible].

7-9 Blackwell, H. Richard. Theory and Measurement of Psychophysical Thresholds. Typed Manuscript. University of Mich.

7-10 Carver, Harry C., Statistical Tables. Edwards Bros., Ann Arbor, Mich. 1940.

7-11 Cochran, William G., and Cox, Gertrude M., Experimental Designs. John Wiley and Sons, New York, N. Y. 1950.

7-12 Collier, G., "Probability of Response and Intertrial Association as Functions of Monocular and Binocular Stimulation." J. Exp. Psychol. Vol. 47. 1954. pp. 75-83.

7-13 Coombs, Clyde H., A Theory of Psychological Scaling. Engineering Research Institute, University of Mich. Bull. No. 34. May 1952.

7-14 Croxton, Frederick E., and Cowden, Dudley, J., Applied General Statistics. Prentice-Hall, New York, N. Y. 1946.

7-15 Deming, W. Edwards, Statistical Adjustment of Data. 1943.

7-16 Edwards, Allen L., Statistical Analysis for Students in Psychology and Education. Rinehart and Company, New York, N. Y. 1946.

7-17 Eisdorfer, C., "A Comparison of Two Methods for the Determination of Visual Recognition Thresholds." Psychol. Newsletter. Vol. 6. 1954. pp. 39-47.

7-18 Engen, T., and Levy, N., "The Influence of Standards on Psychophysical Judgements." Percept. Mot. Skills. Vol. 5. 1955. pp. 193-197.

7-19 Fernberger, Samuel W., "The Use of Equality Judgments in Psychophysical Procedures." Psychol. Rev. Vol. 37, No. 2. March 1930. pp. 107-112.

7-20 Fisher, Ronald A., The Design of Experiments. Hafner Publishing Company, New York, N. Y. 1949.

7-21 Fisher, Ronald A., Statistical Tables for Biological, Agricultural and Medical Research. 1949.

7-22 Garner, W. R. and Hake, Harold W., "The Amount of Information in Absolute Judgments." Psychol. Rev. Vol. 58. No. 6. November 1951. pp. 446-459.

7-23 Graham, C. H., "Behavior, Perception, and the Psychophysical Methods." Psychol. Rev. Vol. 57. March 1950. pp. 108-120.

7-24 Graham, C. H., "Behavior and the Psychophysical Methods: An Analysis of Some Recent Experiments." Psychol. Rev. Vol. 59. January 1952. pp. 62-70.

7-25 Guilford, J. P., Fundamental Statistics in Psychology and Education. McGraw-Hill Book Company. New York, N. Y. 1942.

7-26 Guilford, J. P., Psychometric Methods, Second Edition. McGraw-Hill Book Company, New York, N. Y.

7-27 Hollitch, Robert S., and Hawkes, Albert K., A Catalogue of Devices Useful in Automatic Data Reduction. November 1954.

7-28 [illegible], L., "The Influence of Equality Judgments on the Constant Error." J. Exp. Psychol. Vol. 42. 1951. pp. 300-30[illegible].

7-29 Kogan, Leonard S., "Variance Designs in Psychological Research." Psychol. Bull. Vol. 50. 1953. pp. 1-40.

7-30 Krauskopf, J., The Effects of Retinal Image Motion on Contrast Thresholds. AMRL Project 6-95-20-001, Subtask AMRL S-2, Report No. 221, Dept. of the Army. Office of the Surgeon General, Research & Development Div., Army Medical Research Laboratory. Fort Knox, Ky. January 1956.

7-31 Lewis, Don., Quantitative Methods in Psychology. February 1949.

7-32 McCord, F., The Measurement of Adjustive Eye Movements. Contract N7onr-[illegible]34. T.O. 1, Project NM 001 063.01.31, Joint Project Report 3, Office of Naval Research, Naval School of Aviation Medicine and Tulane University. June 1953.

7-33 MacMartin, Louise S., and Dimmick, Forrest L., Mapping the Central Scotoma of the Dark Adapted Retina: Comparison of a Moving Stimulus with a Stationary Presentation. U. S. Naval Submarine Base, New London, Conn. Med. Research Lab. Report No. 150, Vol. 8: 94-112. 1949. Bur. Med. Project NM 003 041.09.02 (formerly NM 003 024).

7-34 Mueller, Conrad G., "Numerical Transformations in the Analysis of Experimental Data." Psychol. Bull. Vol. 46. 1949. pp. 198-223.

7-35 Von Neumann, John, and Morgenstern, Oskar, Theory of Games and Economic Behavior, Second Edition. Princeton University Press. 1947.

7-36 Newhall, W. M., "Comparability of the Method of Single Stimuli and the Method of Paired Comparisons." Amer. J. Psychol. Vol. 67. 1954. pp. 96-103.

7-37 Ogilvie, John C., and Ryan, J. Eugene, "Threshold Sensitivity to Light Measured with an Extraneous Ultraviolet Source in the Visual Field." J. Opt. Soc. Amer. Vol. 45. No. 3. March 1955. pp. 206-209.

7-38 Peters, Charles C., and Van Voorhis, Walter R., Statistical Procedures and Their Mathematical Bases. 1940.

7-39 Pratt, Carroll C., "The Time-Error in Psychophysical Judgments." Amer. J. Psychol. Vol. 45. April 1933. pp. 292-297.

7-40 Riggs, Lorrin,A., Berry, Richard N., and Wayner, Matthew, "A Comparison of Electric and Psychophysical Determinations of the Spectral Sensitivity of the Human Eye." J. Opt. Soc. Amer. Vol. 39. 1949. pp. 427-436.

7-41 Senders, Virginia L., "Further Analysis of Response Sequences in the Setting of a Psychophysical Experiment." Amer. J. Psychol. Vol. 66. April 1953. pp. 215-228.

7-42 Senders, Virginia L., and Cohen, J., "The Influence of Methodology on Research on Instrument Displays." WADC Tech. Report 53-93. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. Apr'l 1953.

7-43 Smith, W. M., "A Methodological Study of Size-Distance Perception." J. Psychol. Vol 35. 1953. pp. 143-153.

7-44 Stevens, S. S., "Mathematics, Measurement, and Psychophysics." In: S. S. Stevens (Editor) Handbook of Experimental Psychology. John Wiley and Sons, New York, N. Y. 1951.

7-45 Vanderplas, J. M., A Comparison of Four Methods of Measurement of Shape Discrimination. Project 21-09-001. HRRC, Perceptual Research Div., Perceptual and Motor Skills Research Lab. March 1955.

7-46 Verplanck, Wm. S., Collier, George H., and Cotton, John W., "Nonindependence of Successive Responses in Measurements of the Visual Threshold." J. Exp. Psychol. Vol 44 October 1952. pp. 273-282.

7-47 Verplanck, W. S., Cotton, J. W., and Collier, G. H., "Previous Training as a Determinant of Response Dependency at the Threshold." J. Exp. Psychol. Vol 46 No. 1 1953 pp. 10-14.

7-48 Wertheimer, M., "An Investigation of the 'Ran-Domness' of Threshold Measurements." J. Exp. Psychol. Vol. 45. 1953. pp. 294-303.

7-49 Woodrow, Herbert, "The Problem of Quantitative Laws in Psychology." Psychol. Bull Vol. 39. No. 1. January 1942. pp. 1-27.

7-50 Yule, Udny, and Kendall, M. G., An Introduction to the Theory of Statistics. Hafner Publishing Company, New York, N. Y. 1950

CHAPTER 8

VISUAL CAPACITIES, THEIR MEASUREMENT, AND PROBLEMS OF VISUAL PERFORMANCE

All material in the preceding chapters has been presented because it is basic in measuring visual capacities and in using information about visual capacities to attack visual problems in military aviation.

The primary visual capacities are described in this chapter. The ways they are measured are discussed in some detail. Their significance in military aviation is pointed out. From the mass of data presented, four sets of performance data and one set of anatomical data are emphasized by identifying them in the text as "Basic Curves." Although all the data are important in some aspects of military aviation, these five sets seem to offer the most concise way of schematizing a large mass of information about basic visual functions and the variables that affect them and of organizing that information so as to be able to attack and possibly solve the greatest number of visual problems in military aviation. Each set of data shows a different aspect of vision. Each emphasizes the nonlinearity of the visual system. Considered together they demonstrate the complex interactions among visual capacities.

Finally, simple visual problems -- problems in which the primary variables can be identified and manipulated one at a time -- are presented to demonstrate how performance data may be applied to visual problems in military aviation and to provide preparation for the remaining chapters of this book. No one would pretend that applying the five basic sets of data will solve all visual problems that arise. It is entirely possible that applying the data will not completely solve any single problem, but, applying these data will give better problem solution than would be possible without them. Even more important, attempting to apply the data to any particular problem may identify those aspects of the problem for which the data are inadequate and thereby efficiently pin-point critical areas for basic or applied research to produce the data necessary for complete and optimal problem solution.

The visual capacities dealt with are:

1. Light discriminations, consisting of: (a) Brightness sensitivity, the ability to detect a very dim light. (b) Brightness discrimination, the ability to detect a change or difference in the brightness of light sources. (c) Color discrimination, the ability to detect colors. Brightness sensitivity and brightness discrimination are measured in conventional units of intensity, luminance, and brightness. These discriminations vary greatly with the wave length of the stimulus, as well as with the amount of light the observer has previously been exposed to and how long he has been exposed. The sensation of color has components of hue (red, green, etc.), brightness, and saturation (purity of color). Hue discrimination is usually measured in terms of wave length -- as the least difference in wave length that can be detected as a difference in hue. Some 128 different hues can be discriminated by normal observers.

2. Spatial discriminations, the ability to distinguish forms and relationships in space, consisting of: (a) Visual acuity, the ability to see very small objects, to distinguish separate details, or to detect changes in contour, usually measured in terms of the reciprocal of visual angle subtended by the detail. (b) Distance judgment, the ability to judge absolute distance or, more commonly, the relative distance of two or more objects. It is aided by cues learned from experience -- perspective, relative motion, relative size, distribution of light and shade, etc. -- but stereoscopic vision, the disparity of images on the retinae of the two eyes, is the most important factor for very near objects; tests are usually limited to stereoscopic vision, and distance judgment is sometimes expressed as the minimum difference in the angle two objects can make with the two eyes and still be perceived as being at different distances. (c) Form discrimination, the ability to distinguish objects on the basis of shape. It depends to a great extent on the observer's experience and other variables. The goal is to pick out characteristics of shapes that make them easy to distinguish, but only limited success has been achieved in analyzing this type of discrimination. (d) Movement discrimination. Slow movements are detected by difference in location as time passes, but more rapid movements create a single sensation of motion. Measurements are made in terms of minimum angular velocity (with respect to the eye), either relative or absolute, that can be detected. Apparent motion is sometimes seen when there is in fact no motion, as in moving pictures or after a steep bank in an aircraft.

3. Temporal discriminations, arising from the fact that sensations do not follow instantaneously from stimulus changes. The most important is the ability to see flashes of a flickering light as separate rather than as a single, steady light.

LEVELS OF RESPONSE IN VISUAL PERFORMANCE

As we have pointed out, it is convenient to consider visual performance in terms of stimulus and response. By stimulus is meant a characteristic of the energy impinging on the eye. The meaning of response is more complicated, because response occurs at several levels. At the most fundamental level, the response may be taken as the nerve impulses set up when the stimulus acts on the receptor cells of the eye. At the next level, the response would be the sensation produced by the stimulus -- the first awareness of an image, a color, or a light. On a higher level, the sensation combines with memory to create perception -- the first full recognition of what has stimulated the eye. Finally, response may be a movement of the eye, the head, or the entire body in reaction to what has been perceived. Such a common stimulus as a red traffic light produces responses at all four levels. First it sets up impulses in the optic nerve. On arriving at the brain, these impulses give rise to a meaningless color sensation of red. Within a fraction of a second, the driver's memory informs him that this kind of red sensation means he should stop the car; he has now perceived the light. Acting on his perception, the driver raises his foot and puts it on the brake; this action represents the final level of response. When talking about a driver's response to a red light, we may be referring to any or all of the events in this sequence.

By visual performance, we mean the observer's responses at any or all of the four levels. It is therefore important that the kind of response or the kind of performance be specified in every case. The visual scientist, however, is primarily concerned with performance at the sensation and perception levels. If only sensation is involved, changes in performance can be related to changes in the stimulus; as we have seen, one measures this kind of visual performance by measuring the stimulus. At the perception level, however, a "something else" is added to the sensation that may be independent of anything in the stimulus itself. For example, the "something else" in the perception of the traffic light was the meaning of the red light: that the driver must stop. This meaning could not be obtained by measuring or plotting wave lengths, tristimulus colorimetric values, luminance, or any other attribute of the stimulus. Fortunately, however, most kinds of visual performance with which we are concerned can be expressed by measuring related characteristics of the stimulus.

VISUAL CAPACITIES AND THEIR MEASUREMENT

Visual capacities (or kinds of visual performance) are discussed below. Each has been classified according to the stimulus characteristics primarily responsible for it.

Rod and Cone Population Curve

The curve in Figure 8.1 is simply an "anatomical plot" -- a plotting of the actual number of rods and cones per unit of area along a line from the nasal side to the temporal (temple) side of the retina.* Although introduced previously, it is presented here because it provides the anatomical basis for the curves of visual performance that follow. If one knows the part of the retina on which the image will fall in a particular visual task, it is then a simple matter to read this graph and determine the proportion of rods and cones involved. (It can be assumed for most purposes that the density of rods and cones follows the general pattern of curve 1 in all directions outward from the fovea.)

You can see that the density of the cones is very much the same throughout most of the retina, with the exception of two areas: a very small central area in the fovea where the cones increase greatly in number, and an area in the extreme periphery where there is a slight buildup. Rods, however, are more unevenly distributed. They are entirely missing from the very center of the fovea, an area that subtends about one degree of visual angle; they increase in number in all directions out from the fovea, and reach their greatest density at about 18 to 20 degrees from the center. Beyond this region, the rods decrease in number out to the extreme periphery. The other area depicted here is the blind spot -- the optic disk, where the optic nerve leaves the eye. It contains no rods or cones.

*The anatomy of the eye is described in Chapter 3.

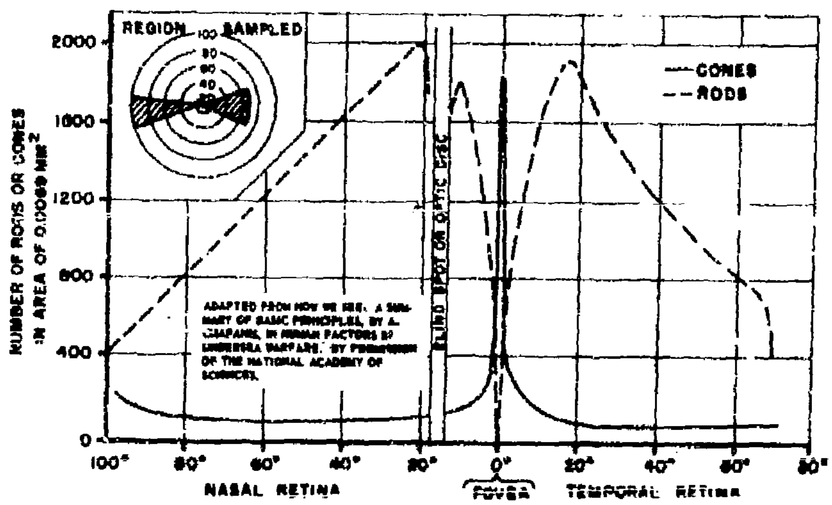


Figure 8.1 Curve 1: Rod-Cone Population Curve -- Density of Rods and Cones From Nasal to Temporal Edge of Retina (after Chapanis [8-5]) (data from Osterberg [8-12])

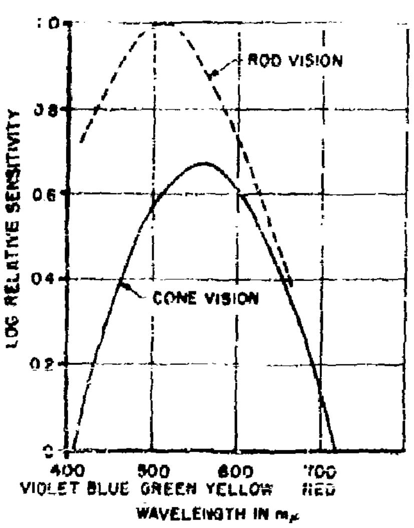


Figure 8.2 Curve 2: Spectral Sensitivity Curve

Relative sensitivity to radiant flux as a function of wavelength (data from Hecht and Williams [8-7])

As was noted in Chapter 3, the cone system is largely responsible for detail and color vision, while the rod system provides for detection of small amounts of light. Different regions of the retina are specialized for these tasks. Detail vision is best in the fovea, where cones are dense, and poor in the periphery of the retina; here rods are more numerous than cones, and sensitivity to small amounts of light is higher than in the fovea.

Light Discriminations

In Chapter 2, it was explained that the sensation of brightness is not just a function of the rate of transmittal of radiant energy, but depends also on the wave length of that energy within the visible spectrum. For this reason, light is measured in arbitrary units based on the international candle and scaled in accordance with the sensitivity of the eye rather than the amount of energy. The eye's ability to respond to radiant energy is limited to a very narrow band of wave lengths.

Spectral Sensitivity Curve (Basic Curve 2). This curve (Fig. 8.2) was chosen because it shows the difference in sensitivity of

the two types of photoreceptors, rods and cones, over the entire visible spectrum; and it shows this difference in a way that removes some of the common misinterpretations that follow easily from other graphical representations of this function.

As we progress from cone vision to rod vision, we see that the region of maximum sensitivity shifts from 555 m μ to 510 mμ. Actually, when luminance is decreased from cone to rod levels, the change from cone to rod functioning occurs gradually. That is, as the eye becomes dark-adapted, sensitivity increases gradually, and the peak wave length becomes shorter. The process could be represented by a series of curves moving up and to the left of the cone-vision curve, with each peak of sensitivity moving closer to 510 mμ. Rods are much more sensitive than cones to radiation from the short-wave end of the spectrum and are about as sensitive as the cones to radiation toward the long-wave end of the spectrum. Generally speaking, the rods require much less radiant energy for vision than the cones; however, the rod response is achromatic (i.e., colorless) while that of the cones is chromatic. Vision of the dark-adapted eye in low level illumination (using only rods) is called scotopic vision. Vision at higher levels (a cone function) is called photopic vision.

The characteristics of the eye described above are often quantified in the form of photopic and scotopic relative luminosity curves, as illustrated in Figure 8.3. The scotopic relative luminosity curve in this figure shows that if someone looked at a very dim, equal-energy spectrum (a light source emitting equal radiant energies at all wave lengths) after spending 30 to 45 minutes in the dark, the different parts of the spectrum would not appear to be equally luminous. The photopic curve shows the relative luminosity of the various wave lengths in an equal-energy spectrum when the intensity of the spectrum is well above cone threshold; the eye has been exposed to a fairly high luminosity level before the measurements for this curve are made. The curves in Figure 8.3 show the sensitivity of the eye under extreme conditions. When the luminance is decreased gradually from photopic to scotopic levels, the transition from cone to rod vision is also gradual.

The different curves in Figure 8.4 were obtained at five luminance levels ranging from cone to rod levels. Notice the gradual shift in the luminosity curves and the increase in the relative luminosity of blue and blue-green lights (wave lengths below about 510 mμ). This shift is called the Purkinje shift, and accounts for the Purkinje phenomenon.

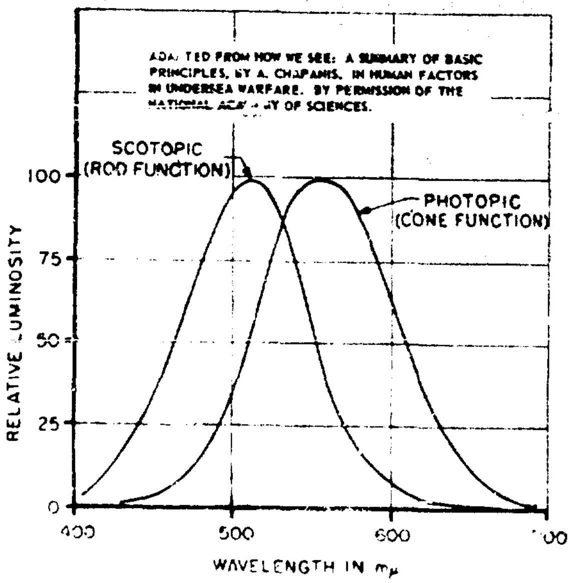


Figure 8.3 Photopic and Scotopic Relative Luminosity Curves

The photopic data are from Gibson and Tyndall; the scotopic data from Hecht and Williams. (after Chapanis, Fig. 5, p. 108-5)

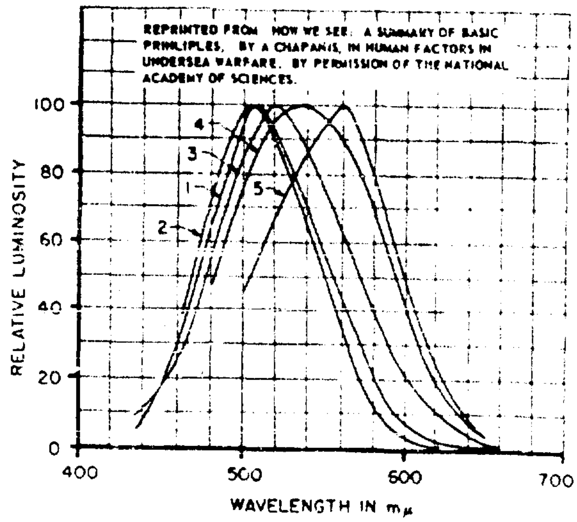


Figure 8.4 Relative Luminosity Curves at Five Luminance Levels

(1 is the lowest luminance; 5 the highest.) The gradual shift in the luminosity curve is called the Purkinje shift. Data from Walters and Wright. (from Chapanis, Fig. 6, p. 118-5)

The photopic and scotopic relative luminosity curves shown in Figure 8.3 are frequently misinterpreted, because it is often not appreciated that each of the curves is drawn relative to its own maximum. This misunderstanding leads to the frequent misstatement that the rods are not as sensitive to the red as are the cones. However, if the relative luminosity curves are replotted in terms of the amounts of energy involved, as is done in Figure 8.5, it can be seen that the rods are about as sensitive as the cones to radiation from the long wave length (red) end of the spectrum up to about 660 $m\mu$.

Brightness Sensitivity. Brightness sensitivity, or the ability to detect a dim light, is of great importance in the detection of objects both inside and outside an aircraft. Below certain intensities and luminances, the eye does not respond at all; the light source is invisible. As the amount of light is increased, a threshold value is obtained at which the eye is just able to detect that light is present. It has been found that the threshold value depends on how much light the subject has been exposed to before the test and how long he has been exposed to that light as well as on other pre-exposure variables; it may be said that the eye is more or less sensitive to light, depending on its state of adaptation to light. Thus, absolute thresholds for light intensity can be measured either to test the maximum brightness sensitivity of the fully adapted eye or to determine the degrees of adaptation to darkness or to any level of brightness as a function of related variables.

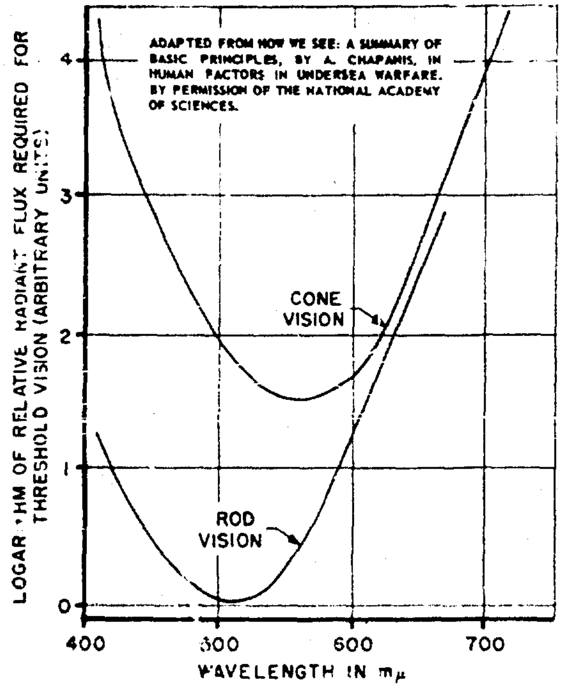


Figure 8.5 Relative Amounts of Radiant Flux Required to Stimulate the Rods and Cones

These curves are replotted from data in Fig. 8.3. (after Chapanis, Fig. 7, p. 12 8-5)

The usual procedure for measuring the sensitivity of a dark-adapted eye is to light-adapt the eye first by exposing it to a known high level of illumination for a specified period of time (this is called pre-adaptation). This procedure insures that conditions will be equal for all subjects at the beginning of dark adaptation. Then, seated in darkness, each subject is given tests at regular intervals (one-minute intervals are often used, although much shorter times are used at the beginning of dark adaptation) as he becomes dark-adapted. Each test consists of a series of brief flashes of a light (one flash may be made about every 3 seconds), the brightness of the stimulus is increased with each exposure until the subject first reports that he can see it (ascending series of method of limits), or the brightness is decreased until the subject first fails to see it (descending series). This procedure is continued at intervals for some 30 or 40 minutes, until adaptation is complete. The successive thresholds thus obtained, when plotted against adaptation time, yield a curve of dark adaptation. Brightness sensitivity, of course, increases (and the threshold decreases) with dark-adaptation time.

Somewhat the same procedures are used to obtain a light-adaptation curve -- a curve that shows the lowest brightness level the eye can respond to after various periods of exposure to light of some constant brightness. The subject is first dark-adapted for at least 10 minutes; then he is stimulated with an evenly lighted field of a specified brightness. At various intervals this "adapting" light field is turned off, and a test object is flashed in the dark at a low brightness level. The subject reports whether or not he sees it. The cycle is repeated until many measurements have been taken over a series of time intervals. A light-adaption curve is then plotted. This curve will be different from a dark-adaptation curve. That is, the brightness sensitivity will decrease (and the absolute threshold will increase) with time of exposure to light.

Test objects are generally small circles or squares. Sometimes a broken ring like the letter C is used; the subject is required to locate the break, so that the tester can check whether the subject actually sees the object. To be sure that the same portion of the retina is stimulated in each trial, the subject is generally given some object to fixate when the stimulus is not visible. To eliminate variability due to head movement, the subject may be given a chin rest or a biting bar (which may even be wax impression of the subject's own teeth).

Dark-Adaptation Curve (Basic Curve 3). This dark-adaptation curve (Fig. 8.6) has been selected as one of the basic curves of visual performance, because it illustrates part of the tremendous sensitivity range of the eye, and also illustrates how the eye's sensitivity behaves as a function of time in the dark.

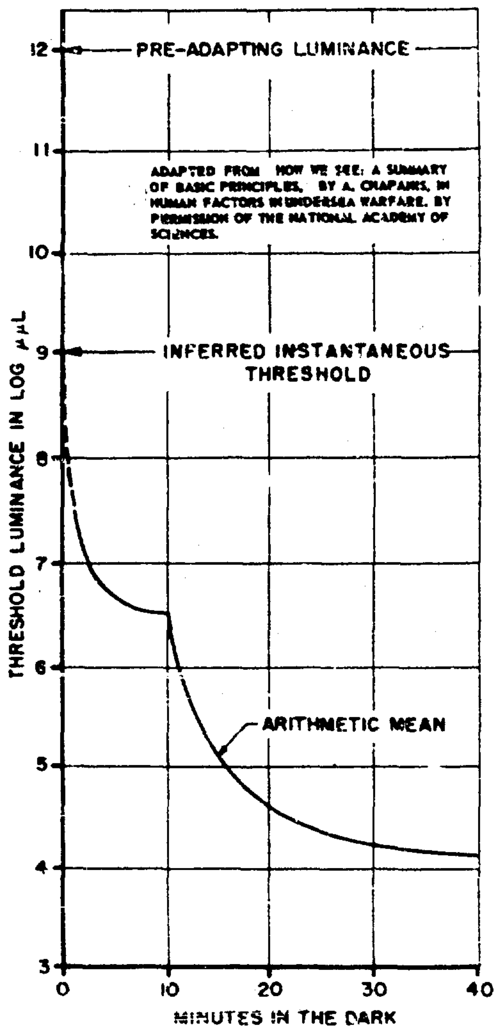


Figure 8.6 Curve 3: Dark-Adaptation Curve

Increase in ability to see, measured as luminance that can just be seen as a function of time after lights are turned out. (after Chapanis[8-5])(data from Sloan [8-13])

Note: While the luminance of an extended source is strictly speaking the light emitted per unit of area per unit of solid angle, and brightness is the visual sensation in response to luminance, they can usually be taken to mean the same thing for extended sources or reflectors of light. (Any source of finite size is considered "extended.") Both are designated by B. It will be remembered from Chapter 2 that 1 lambert is the brightness of a perfectly diffusing surface emitting 1 lumen/cm^2. Lamberts can be used to designate the brightness of surfaces that are not perfectly diffusing if they

appear as bright as a perfectly diffusing surface from some viewing angle (in this case, the angle should be indicated). One millilambert = 10^{-3} lamberts; it is the most commonly used unit for measurements of brightness. For very low levels, the micromillilambert (μ mL) is sometimes used; 1 μmL = 10^{-9} lamberts. However, since the sensation of brightness is usually roughly proportional to $\log_{10}$ of the brightness value, measured values are often converted to $\log_{10}$ micromicrolamberts ($\log_{10}\mu\mu$L) (1 $\mu\mu$L = 10^{-12} lamberts) for plotting curves such as Figure 8.6. It can be seen that 4 log units = 10,000 $\mu\mu$L = 10^{-5}mL; 5 log units = 10^{-4} mL, etc.

It is interesting to note that the darkadaptation curve in Figure 8.6 has two distinct parts. The first begins with a very rapid decrease in the threshold and ends with a leveling off after about 10 minutes in the dark. The value during this leveling off period represents the lowest cone threshold -- the dimmest light that can be seen with cone vision when the cones (i.e., *the foveal receptors*) are fully adapted. In general, the cones will respond to a range of brightness from about 0.004 mL up to about 10,000 mL. The second segment begins at about 10 minutes and continues up to a final leveling off, which occurs anywhere from 35 to 45 minutes after adaptation has begun; this final value represents the lowest rod threshold. The rods respond to a range of brightness from about 0.004 mL down to 0.00001 mL. Colors can usually be recognized during the decrease in threshold that occurs as cone sensitivity increases during the first eight or nine minutes of adaptation. However, during the second decrease in threshold due to the increase in the rod sensitivity, colors are no longer recognizable; a test light of any color always appears achromatic although the threshold obtained will still be a function of the color of the test light.

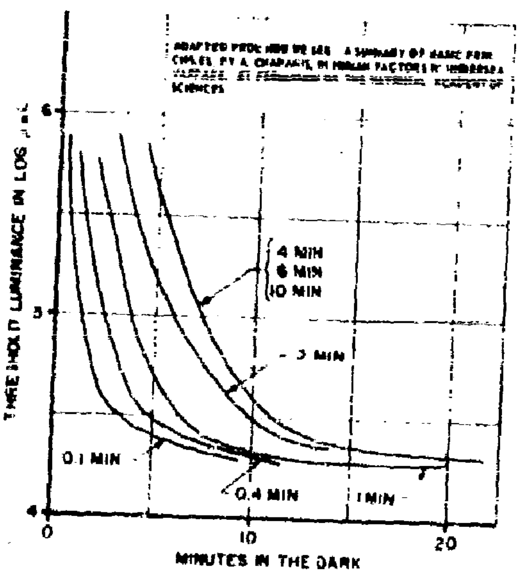


Figure 8.7 Dark Adaptation as a Function of Duration of Previous Light

Darkadaptation curves for one subject following exposure to light of 447 mL for various durations. Only the rod portions of the curves are shown here. (after Chapanis, Fig. 12, p. 189-5) (data from Haig)

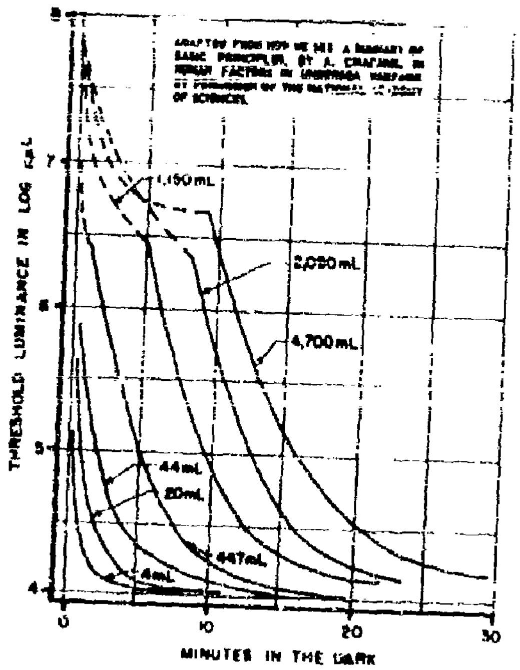


Figure 8.8 Dark Adaptation as a Function of Intensity of Previous Light

Dark-adaptation curves for one subject following exposures to lights of various luminances for four minutes. The broken lines indicate the color of the test light (violet could be identified at threshold. (after Chapanis, Fig. 10, p. 178-5) (data from Haig)

Light sensitivity at a given moment depends on the length of time the eye has been exposed to a certain level of illumination. Other factors that influence absolute sensitivity to light are: (1) the duration and (2) intensity of previous light, (3) the size of the test object, (4) the color of the pre-exposure and the test light used for measuring sensitivity, and (5) the region of the retina stimulated. When we measure the effect of these variables on dark adaptation, we get curves such as Figures 8.7 through 8.11.

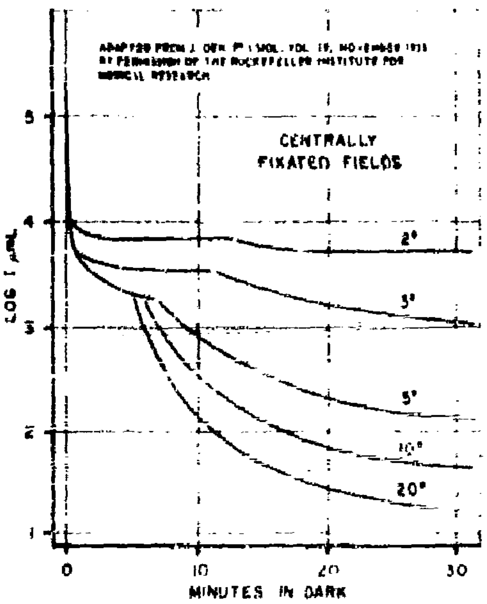


Figure 8.9 Dark Adaptation as a Function of the Area of the Test Object

Dark-adaptation curves for centrally fixated areas of different size. (after Stevens, Fig. 17, p. 947[8-15]) (data from Hecht et al)

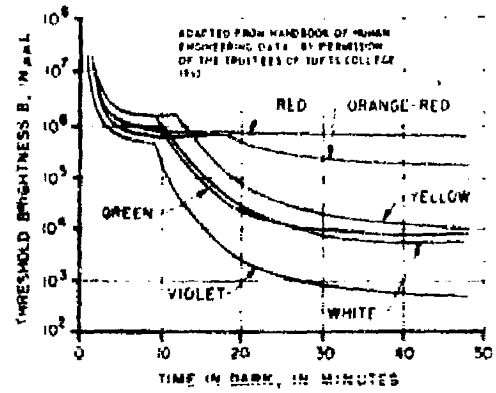


Figure 8.10 Dark Adaptation as a Function of the Wave Length of the Test Stimulus

Dark-adaptation curves measured with lights of different wave lengths. Although lights were equated in brightness initially, they are no longer equally bright even at cone threshold. The differences are further exaggerated during rod dark adaptation. (after Tufts Handbook[8-1]) (data from Chapanis)

<u>Dark Adaptation in Aviation</u>. It has been pointed out that both the rod and cone receptors in the retina dark-adapt, but dark-adapted rods are much more sensitive to low levels of illumination than dark-adapted cones -- that is, we can detect much dimmer lights with rods than with cones. On the other hand, fine visual acuity and perception of color require cone vision. So, although the rods are very sensitive to light, pure rod vision is suited only for seeing outlines and large contrasts; for more acute vision, we must have enough light to stimulate the cones. In dealing with dark adaptation for flying, one must therefore take into account the kind of vision required on the mission.

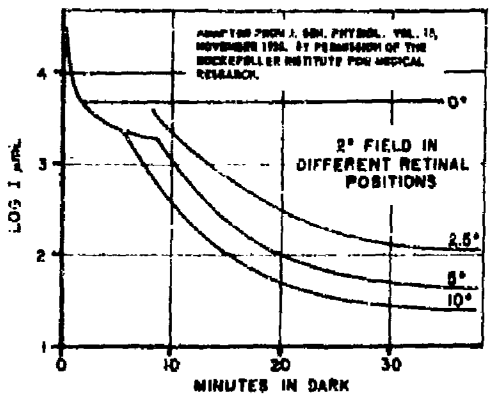


Figure 8.11 Dark Adaptation as a Function of the Region of the Retina Stimulated

Dark-adaptation curves measured with a 2-degree test object placed at various angular distances from the fixation point (after Stevens, Fig. 18, p. 9478-15) (data from Hecht, Haig and Wald)

Whenever a pilot must look into the dark outside his aircraft and obtain information through vision, some degree of dark adaptation is required. When very dim or very distant lights must be located, or when large outlines are to be spotted, such as the profile of a mountain against the night sky or the blurred outline of a nearby aircraft, rod vision is required. On the other hand, if details or color must be seen, such as distant aircraft and aircraft markings, runway markers, details of terrain, and the like, then cone vision is required; in this case, adaptation to maximum rod sensitivity may be superfluous.

Let us first suppose that the operational situation requires complete <u>rod</u> adaptation. This condition can be obtained if the pilot or crewman is completely protected from any light stimulation for at least thirty minutes before the flight. Staying in a completely dark room and wearing a tight blindfold are the most certain ways of obtaining rod adaptation.

However, keeping a man blind before flight prevents him from making final checks, reading charts and weather maps, and other essential activities. It has been found that a pilot or crewman can avoid these difficulties and still obtain a satisfactory degree of dark adaptation if he is exposed only to red light for some thirty minutes before flight. To understand this, look at the red end of the sensitivity curve, Figure 8.2. Note that at 600 mμ the rods and cones are about equally sensitive*, but the cones are nearly at their highest possible sensitivity, while the rods are capable of much greater sensitivity to light around 500 mμ. Thus, red light, which is adequate for good cone vision (permitting reading and other activities while adapting), has relatively little effect on rod adaptation. Hence, wearing red goggles for 30 minutes before take-off, or staying in a ready room with red illumination, gives a pilot or crewman satisfactory rod adaptation for night flying.

However, the situation is quite different in preparing for night operations requiring maximum <u>cone</u> adaptation. As we have just noted, cones are relatively sensitive to red light; for practical purposes, the cones can become just as dark-adapted in white illumination as in red illumination of the same brightness.

The rate at which cones achieve maximum sensitivity depends on the brightness of the light to which they have been exposed and the length of time they have been exposed to it. The time that one should allow for dark adaptation also depends on the level of sensitivity to be attained. However, cones reach peak sensitivity to brightness after only five to ten minutes in complete darkness, even after exposure to high levels of illumination.

After the cones are fully dark-adapted, they can be exposed to low brightness for a short time and then regain full dark adaptation almost immediately -- within five to ten seconds after a return

*This is contrary to the fairly common misconception that rods are not at all sensitive to red light.

to darkness. For example, if a pilot looks at a chart for a short time under low illumination, his cone sensitivity for objects in the night sky is fully restored in a few seconds. By a "short time" and "low brightness" we mean exposure to something less than 100 foot-lambert-seconds.[8-9] (One hundred ft-L-sec = exposure to 10 ft-L for 10 sec, to 100 ft-L for 1 sec, etc. Ten foot-lamberts can be thought of as roughly the brightness of a sheet of white writing paper illuminated by a 10-watt bulb at a distance of one foot.) Furthermore, if the fovea has been adapted to a low brightness somewhat above complete darkness -- 0.1 or 1 foot-lambert, for example -- it can be exposed to a small additional brightness (again perhaps up to 100 ft-L-sec) without basically altering its sensitivity.[8-10]

Dark adaptation of the rods (i.e., the area outside the fovea) is a different matter. As indicated above, some 30 minutes in darkness or in red illumination are needed for maximum rod sensitivity. Furthermore, dark adaptation of the rods is harmed to a much greater extent than dark adaptation of the cones by a brief exposure to low illumination. Exposure of the rods to 100-ft-L-sec causes a large loss of sensitivity; at least two minutes in the dark is required to recover it.[8-8] To complicate matters, sensitivity differs at different locations in the periphery of the retina. At 2 degrees from the fovea, exposure to as little as 0.01 ft-L-sec produces a measurable decrease in sensitivity. At 6 and 18 degrees, on the other hand, there appears to be little loss in sensitivity after exposure to as much as 0.1 ft-L-sec.

In summary, then, the following preflight procedures will ensure that pilot and crew are sufficiently dark-adapted in flight: (1) If a pilot or crewman must detect dim lights or dark objects in flight, he should wear tight-fitting red goggles or be exposed only to red illumination for at least a half hour before flight. He should not be exposed to any other kind of illumination for even an instant. (2) If cone vision is to be used in flight -- if pilot or crewman must discriminate small objects or fine detail -- five to ten minutes in 0.005 to 0.01 foot-lambert of white light will provide enough adaptation. In this case, brief exposures to somewhat higher illumination will do little harm.

It should also be remembered that dark adaptation must be maintained in flight. Thirty minutes of preflight rod adaptation is useless if the cockpit instruments are illuminated with, say, one foot-lambert of white light. On the other hand, there is no such thing as overadaptation in night flying. That is, cone vision is in no way impaired by 30 minutes of dark adaptation for maximum rod sensitivity. In other words, when in doubt, adapt for 30 minutes in red illumination.

Brightness Discrimination. Brightness discrimination is the ability to detect small changes in the amount of light or small differences between two light sources. Above the threshold values at which light can just be seen, the eye can discriminate small changes or differences in intensity. Measurement of brightness discrimination is made by obtaining differential thresholds. Usually, investigators test the ability to discriminate whether a difference exists between two light sources seen side by side. In general, the method is to present a test field and a comparison field so that they touch. Either the test field is surrounded by the comparison field or a split field is presented, half test and half comparison. When the test and the comparison fields are equally bright, the two fields are indistinguishable -- that is, the border between them tends to disappear. If the test field is made brighter or dimmer, a point will be reached where the fields can just be distinguished, and the difference in luminance is the difference threshold.

When an object is viewed against an illuminated background of the same hue, the difference between the brightness of the object and its background must be above the difference threshold before the object can be seen. The relationship between these brightnesses is called brightness contrast.

Contrast Discrimination Curve (Basic Curve 4). Expressed as a percent, contrast is equal to $\Delta B/B \times 100$, where ΔB is the difference in luminance between object and background and B is luminance of background. Curve 4 of Figure 8.12 shows that the threshold contrast -- the least contrast required for an object to be detected against its background -- decreases as luminance increases, until it reaches a limit at a high illumination (in the order of 100 millilamberts). This means that the capacity of the human eye to detect differences in the brightness of objects increases as illumination increases. Note that contrast discrimination also

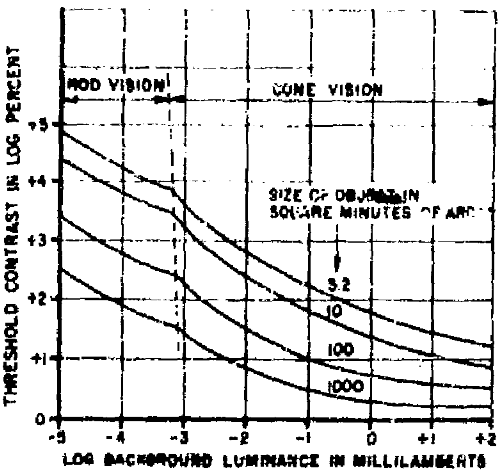


Figure 8.12 Curve 4: Contrast Discrimination Curve -- The Smallest Brightness Contrast That Can be Seen, as a Function of Background Luminance

Curves for test objects of four sizes are shown. (after Baker & Grether[8-3]) (data from Blackwell)

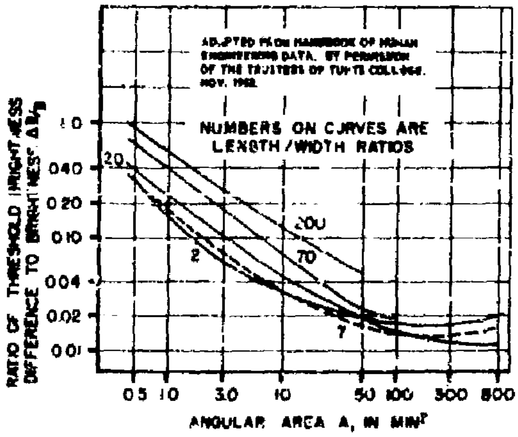


Figure 8.13 Contrast Threshold as a Function of Shape of the Stimulus

Effect of area of rectangular stimulus on threshold contrast $\Delta B/B$ for 5 ratios of length to width of rectangle. For large areas, threshold contrast for fixed area decreases as shape approaches square. When area exceeds 100 min, shape again becomes unimportant. (after Handbook, T2-2C, data of Lamar et al[8-1])

increases with the size of the test object. The sharp discontinuity in the curves occurs at the luminance values where the eye shifts from rod vision to cone vision.

The contrast threshold is affected not only by such properties of the stimulus as intensity of illumination and size of the test object, but also by the (1) shape of the stimulus, (2) wave length of the stimulus, and (3) region of the retina stimulated. The curves in Figures 8.13 through 8.15 illustrate these factors.

Color Discrimination

In Chapter 2, we pointed out that the sensation of color consists of at least three components complexly related to physical characteristics of the stimulus and to the illuminant under which the stimulus is viewed. These components are hue, saturation, and brightness. The hue of an object -- whether it is red, green, violet, etc. -- is most closely related to the dominant wave length of the light it emits or reflects; this relationship can be seen when sunlight is split into components of different wave lengths by passing it through a slit and a prism. Saturation, the purity of a color, is related to the amount of white light mixed in with the color; it often depends in large part on the type and amount of illuminant. Brightness is related to the rate of transfer of luminous energy -- the lumens per sterdian per unit of area, or the lamberts. We also explained in Chapter 2 that color is usually specified in terms of all three components, the most common systems being a tristimulus system such as the ICI or a color solid such as the Munsell solid. Methods of measuring the three components are described separately below. However, since the three interact to some extent -- for example, a bright red will appear to be a different hue than a dull red of the same wave length -- one must be careful when measuring one component to keep the other two as nearly constant as possible. Conversely, as we pointed out in Chapter 2, the equipment designer must think of more than the spectral color if he aims at making objects, dials, or chart readings stand out. He must choose a color that will be bright enough to be legible under all conditions and that will be visible under any type of illumination that is to be used. (Important markings on some aeronautical charts, for example, simply vanish under red light.)

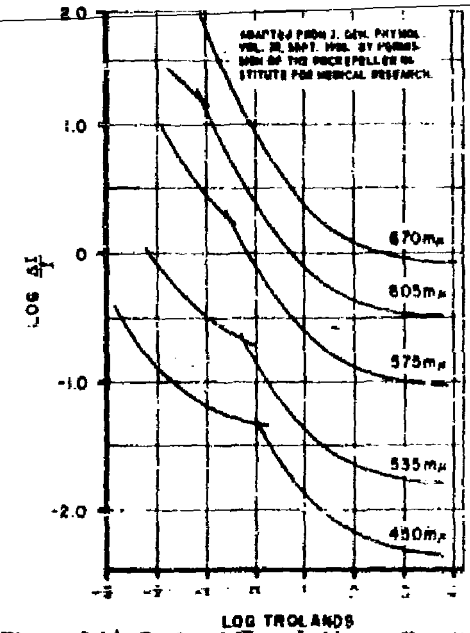


Figure 8.14 Contrast Threshold as a Function of Wavelength of Stimulus

Brightness discrimination for the red, orange, yellow, green and blue parts of the spectrum. The labelling on the ordinate applies to the data for yellow (575 mμ). The orange and red curves have been raised 0.5 and 1.0 log unit respectively, and those for green and blue have been lowered 0.5 and 1.0 log unit respectively. (after Stevens, Fig. 36, p. 957) (data of Hecht et al[8-15])

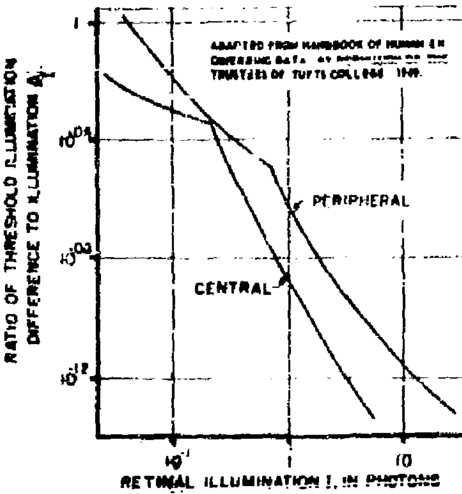


Figure 8.15 Contrast Threshold as a Function of Region of the Retina Stimulated

Just noticeable difference in retinal illumination as influenced by illumination for foveal and peripheral vision. In peripheral vision, where rods predominate, transition from rod to cone vision occurs at higher illumination level. Discrimination is generally poorer in periphery than in center of visual field. (after Handbook, T2-2d, data of Steinhardt[8-1])

Hue Discrimination. In testing the ability to discriminate hues, the chief interest lies in what hues can be discriminated rather than in whether a particular hue can be seen. Hue discrimination is usually measured in terms of the smallest difference in wave length that two test fields can have and still be interpreted as of different hues. The subjects in the test start at one end of the visible spectrum and work through to the other end. The procedure is to start with two comparison fields receiving the same wave length. The wave length of one field is changed until the observer can detect that a hue difference exists between the two fields. Next, a third hue that can just be distinguished from the second is established, and the procedure is continued until all the distinguishable hues in the spectrum have been covered. With good illumination and saturated colors, some 128 hues can be distinguished on the basis of this kind of comparison, but the eye's response is by no means proportional to wave length; the ability of the eye to discriminate hues varies considerably with the portion of the visible spectrum involved. It is greatest at two separate parts of the spectrum, the blue-green and yellow (Fig. 8.16); here, wave-length differences as small as a millimicron can be discriminated as separate hues. At the red (long-wave) end, the difference must be as great as 20 millimicrons before it is detected. The number of hues that can be discriminated on a single presentation, without any comparison hue, is, of course, considerably smaller than 128.

Brightness Discrimination and Sensitivity. General methods for measuring brightness discrimination and sensitivity have been described above. The same methods are used to measure the effects of brightness as a parameter of color.

In this case, hue and saturation are kept constant in each test, and only the luminance of the field is varied. By repeating the test for different hues, either the just visible threshold or the ability to discriminate between two different brightnesses can be plotted as a function of hue or wave length on the visible spectrum. As illustrated in basic curve 2 (Fig. 8.2), brightness sensitivity is the greatest for colors near the center of the visible spectrum. Sensitivity for cone vision is greatest at some 550 millimicrons (in the yellow-green portion), while sensitivity for rod vision is greatest at somewhat shorter wave lengths, in the blue-green portion.

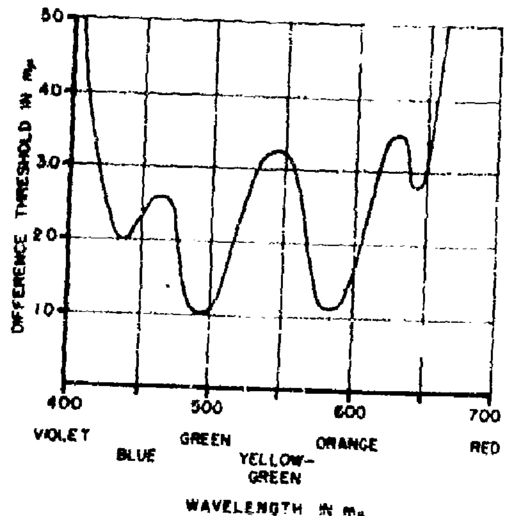


Figure 8.16 Smallest Difference in Wavelength That Can be Detected as a Difference in Hue When Two Fields are Presented for Comparison (Average of data from Steindler[8-14] and Jones[8-11])

<u>Saturation Discrimination.</u> Saturation discrimination is difficult to study with exactness, and little work has been done in this field. A major difficulty is that as saturation is decreased -- that is, as white light is added -- the sensation of hue also changes (except with colors in the yellow-green portion of the spectrum). To measure saturation discrimination, two identically saturated fields may be presented, and the saturation of one varied until the observer notes when he detects a change. The results may be expressed in terms of percentage of white light.

Note that in Chapter 2 we were concerned chiefly with methods of identifying color -- of specifying its components so that persons trying to describe or use color with exactness can talk the same language. In this chapter, we have been concerned with the ability to discriminate differences in each of the components. Color specification and discrimination are not the same thing, but they are interdependent; for example, the ICI tristimulus values were arrived at by psychophysical tests of hue discrimination like those described here.

Spatial Discriminations

Visual stimulation consists largely of light striking the light-sensitive tissues of the retina. Differences in the wave lengths and intensities of the light that strikes different areas of the retina give outline and form to images. Good vision consists in large part of the ability to see these images sharply and judge their locations and relationships in space. This ability is broadly classed as spatial discrimination, and it includes four major categories of visual performance: <u>visual acuity</u>, <u>depth discrimination</u>, <u>form discrimination</u>, and <u>movement discrimination</u>. They are described in the pages that follow. Note that they are tested with lines, dots, point sources of light, and abstract shapes; one strives to prevent the observer's experience from introducing large and unspecified variables. In "real life," of course, experience often helps a person judge relationship and form when the retinal images are blurred; the myopic taxi driver twists safely through narrow openings, while his clear-sighted passenger keeps bracing himself for the crash that his eyes tell him is inevitable.

<u>Visual Acuity</u>. Visual acuity may be defined very generally as the ability of the eye to see fine details. It may also be thought of as the resolving power of the retina for various kinds of details of the image. Visual acuity is influenced by the refractive state of the eye. There are four distinct measures (or types) of visual acuity, which are used in discriminating four different aspects of detail. The types are minimum visible, minimum perceptible, minimum separable, and minimum distinguishable acuity. The values obtained in tests differ widely for the different types of acuity. Therefore, one should not apply visual acuity data to any situation until he is sure the data were obtained for the type of acuity required in that situation.

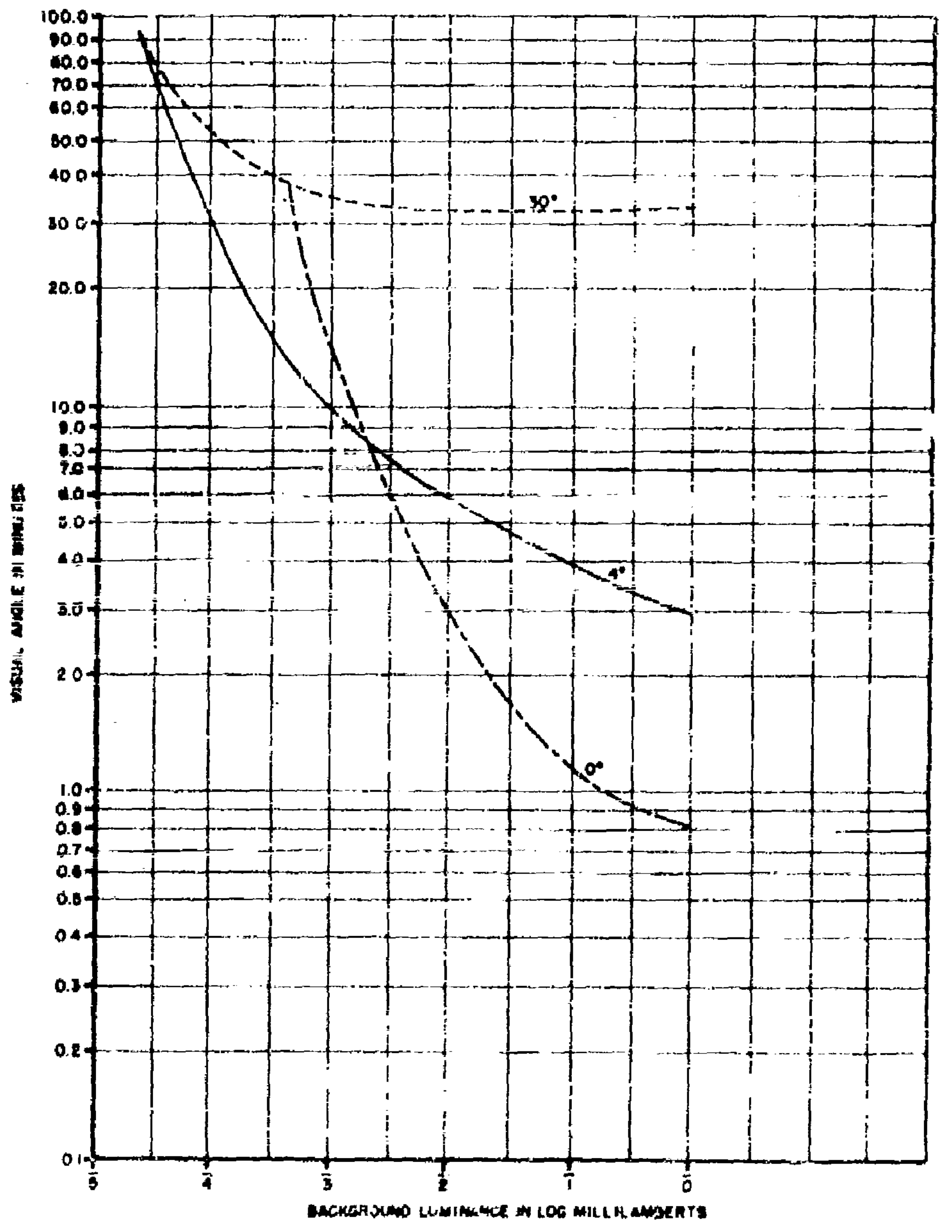


Figure 8.17 Curve 5: Visual Acuity Curve. Visual Angle Subtended by Smallest Detail That Can be Discriminated, Plotted as a Function of Background Luminance

Curves are shown for discriminating images at 0°, 4°, and 30° away from visual axis on retina. (data from Mandelbaum and Rowland[8-28])

Minimum visible acuity refers to the ability to see a point source of light. Since by definition a point source is infinitely small, its size cannot be varied. Therefore, its intensity chiefly determines whether it can be seen or not.

Minimum perceptible acuity is the ability to see small objects against a plain background. It is most commonly tested with fine black wires or small black dots against illuminated white backgrounds. In minimum perceptible acuity, the size of the object -- that is, the angle it subtends at the eye -- becomes the determining factor (assuming that illumination and other variables are held constant).

Minimum separable acuity defines the ability to see objects as separate when they are close together. It is measured as a function of the least distance that two objects of the same size and shape can be placed apart and still be seen as separate. Both luminous and nonluminous objects of various sizes and shapes are used for tests. Sometimes a line with a gap is used; the smallest gap that can be recognized determines minimum separable acuity. Sometimes a grating of parallel lines or bars is used; as the grating is rotated so that it becomes more nearly end on to the observer, the bars appear to come closer together. In this case, minimum separable acuity may be expressed as the largest angle of rotation at which the bars can still be seen as separate in a standard grating at a standard distance from the observer.

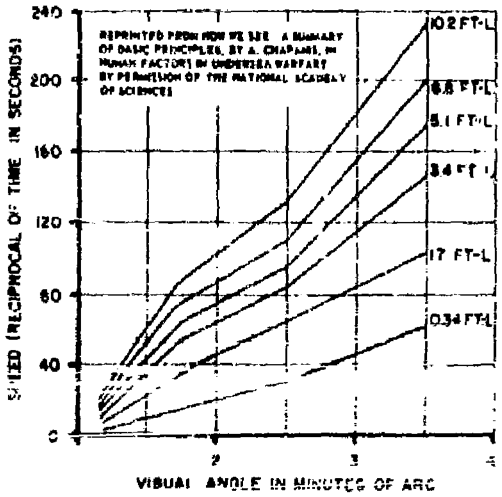


Figure 8.18 Visual Acuity as a Function of Time

At any luminance level, less time is required to see bigger objects. When size is held constant, less time is required to see at higher luminance levels. (from Chapanis, Fig. 20, p. 30 8-16) (data from Ferree and Rand)

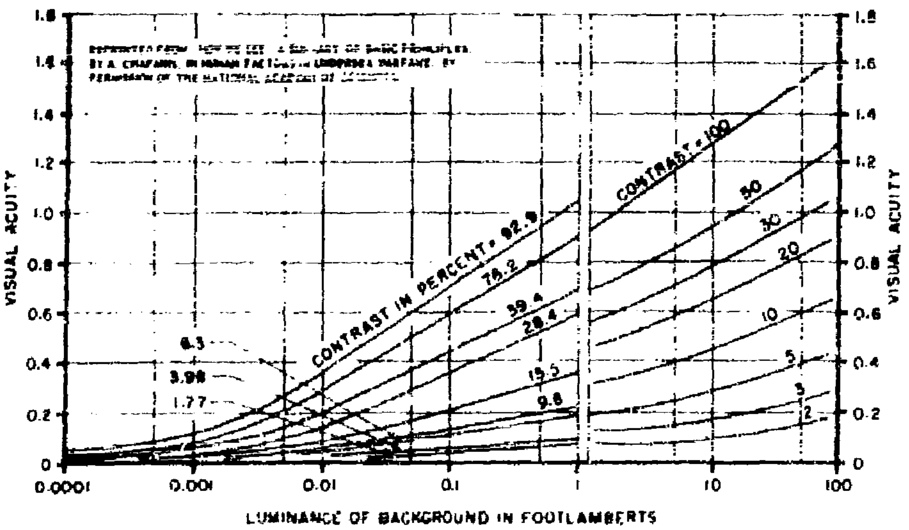


Figure 8.19 Visual Acuity as a Function of Contrast

Visual acuity as a function of background luminance and the luminance contrast between the object and its background. The data on the left are from Connor and Ganoung; those on the right from Cobb and Moss (from Chapanis, Fig. 21, p. 31 8-16)

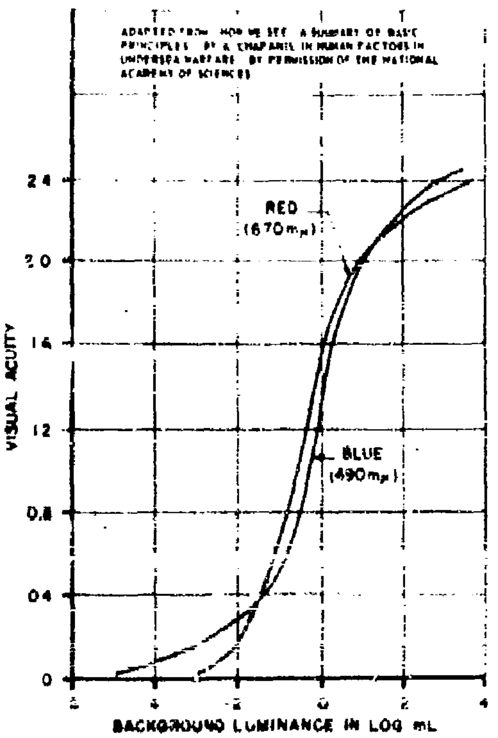


Figure 8.20 Visual Acuity as a Function of Color of Illumination

Visual acuity with red and blue backgrounds of various luminances (after Chapanis, Fig. 26, p. 37 [8-15]) (data of Shlaer et al)

Minimum distinguishable acuity is the ability to distinguish irregularities and discontinuities in the contours of an object. It is sometimes called form sense. Sometimes a ring with a small break in it is used for tests; the observer is asked to locate the break. The Landolt C of standard proportions is commonly used. Vernier acuity, a special type of minimum distinguishable acuity, refers to the ability to recognize that two lines drawn end to end are slightly offset from each other.

Units of Visual Acuity. Visual acuity is commonly expressed as the *reciprocal* of the minutes of visual angle subtended by the detail being discriminated. The advantages of expressing acuity in terms of subtended angle are: (1) All kinds of visual acuity (except minimum visible) can be measured in this way. (2) The angle can be calculated easily for test devices commonly used -- bars, broken rings, gratings, fine wires, and dots. (3) Results obtained for near objects are expressed in the same units as results for distant objects; the data for one can be applied to the other, provided such factors as accommodation and haze are taken into account. The reciprocal of the angle is used rather than the angle itself so that good visual acuity will have a higher value assigned to it than poor visual acuity (the larger the angle that must be subtended for detail to be seen, the worse the acuity).

For clinical purposes, as for example for judging the visual acuity of inductees into the armed services, and the like, the individual's visual acuity is often expressed as a ratio to normal acuity. For this purpose, a Snellen chart compound of Snellen letters of standard proportions and sizes is commonly used to measure a complex form of acuity probably most nearly related to minimum separable acuity. The ratio used is

$$\frac{\text{distance at which individual can discriminate a particular detail}}{\text{distance at which normal eye can discriminate same detail}}$$

Thus, 20/20 vision means that the individual can discriminate an object at 20 feet that the normal eye also discriminates at 20 feet; 20/10 is better than normal -- the individual can see an object at 20 feet that the normal eye can only see at 10 feet -- while 20/40, 20/80, etc. are successively worse than normal.

Mean normal vision can discriminate a detail subtending approximately one minute of visual angle, so the discrimination of 1 minute of visual angle is taken as normal. Expressed in reciprocal of angle, 20/20 vision is therefore a visual acuity of 1.00, and 20/40 is 0.50.

Conventional wall charts, with rows of letters or symbols of varying size, are devices for the rapid measurement of visual acuity. Such charts do not measure acuity precisely. They are suitable for discovering differences in acuity among individuals or between an individual and the normal eye such as occur as a result of refractive errors. For research purposes, where the objective is to discover what variables affect acuity and how much they affect it, more precise equipment and procedures are needed. Commercial devices such as the orthorators, adaptometers, and discriminometers embody the test objects described above (in the discussion of different types of acuity). Often, however, the research worker must design special, highly precise equipment for measuring a particular variable.

Visual Acuity Curve (Basic Curve 5). Visual acuity may be measured and plotted as a function of a number of variables. The graph in Figure 8.17 which relates acuity to luminance and the retinal location of the image, was chosen because we have already met these variables in curves 1, 2, and 3.

With foveal vision (0 degrees on the retina), no values were obtained at background luminances of less than -4.6 log units; this indicates that no objects at all can be seen with cone vision at very low luminances. From -4.6 log units up, however, foveal acuity increases very rapidly (that is, the eye can discriminate increasingly smaller details) until background luminance approaches 1 millilambert (0 log units). Here, the curve levels off, and acuity improves little or not at all with further increases in luminance. At both 4 and 30 degrees from the fovea, large objects can be discerned at very low luminance values. However, at 30°, there is no further improvement in acuity at luminance values just above those where foveal (0-degree) vision begins, and the smallest angle that can be discriminated in this region of the retina never gets smaller than 30 minutes. At 4 degrees, on the other hand, acuity gets better with increased luminance up to about 1 millilambert; at this luminance it is not strikingly worse than foveal acuity: 3 minutes of visual angle can be discriminated at 4 degrees, against 1 minute at the fovea. These results might be predicted from curve 1 (Fig. 8.1), which shows that rods predominate at both 4 and 30 degrees, but there are more cones at 4 degrees than at 30 degrees.

At the lower background luminances, best visual acuity is obtained at about 4 degrees from the fovea.

Basic curve 5 shows that visual acuity varies as a function of luminance and retinal location. Other factors affecting visual acuity are (1) exposure duration (Fig. 8.18), (2) contrast between the object and its background (Fig. 8.19), and (3) color of illumination (Fig. 8.20).

Distance Judgment. The terms "distance judgment" and "depth perception" are both used to describe an estimate of the distance of an object from the observer or the relative distance of two or more objects. The term "distance judgment" is used here because the word depth, with its implication of vertical distance only, is misleading, and the word judgment conveys better than the word perception the idea of estimating, in miles or other units, the distance of a single object; this problem is more common in aviation than the determination of the order of proximity of several objects. Also, the term "depth perception" has sometimes been limited to the estimation of distance from the single cue of stereopsis. In military aviation, distance judgment is required:

1. In low-altitude attack of ground targets, to estimate the distance to the ground to avoid collision.

2. In air attacks, to estimate distance to other aircraft.

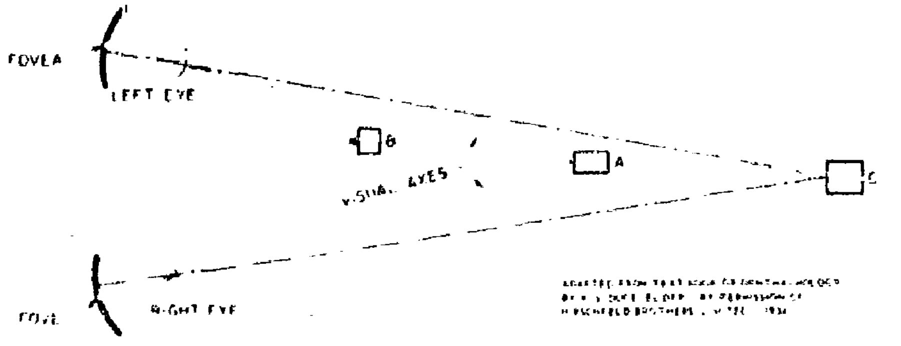


Figure 8.21 Stereoscopic Vision

Object A is in focus, but the two eyes see it from different angles. The images of object B appear crossed while those of C appear uncrossed.

3. In formation flying, to estimate the distance to other aircraft.

4. In landing operations, to estimate the distance to the runway in setting up the downwind leg, the base leg, and the final approach in the traffic pattern. It is needed most critically to judge height above the runway, in order to determine when to flare out and when to reduce power for touchdown.

5. In take-off, to judge height above runway.

6. In avoiding air collisions.

7. In avoiding taxiing collisions.

8. In navigation, to judge the distance of checkpoints, etc.

9. In judging distance to controls inside the cockpit.

10. In air-to-air refueling, judging the distance of ground objects in reconnaissance, and in many other applications.

Cues. The judgment of distance depends on many cues. The judgment is a weighing and a summation of these cues, mostly without conscious thought as to the methods or reasons for arriving at the judgment. The value of most of these cues is learned from experience, but on a subconscious level; however, this does not mean they cannot be consciously taught, and it is highly probable that training and practice improve distance judgment.

There are ten well-defined cues in distance judgment. Two of these are binocular; that is, they depend on the two eyes being slightly separated as they view an object. The other eight are monocular; they work with one eye as well as with two eyes.

Of the binocular cues, much the most important is stereopsis, or stereoscopic vision. It is based on the facts that (1) objects viewed with both eyes are viewed from slightly different angles and form slightly different images on the two retinas, and (2) objects nearer than a fixated object form crossed images in the two eyes, while objects farther away form uncrossed images. These points are shown in exaggerated schematic form in Figure 8.21. The eyes are focused on the object at A. The image of A falls on corresponding points on the foveas of the two eyes. However, the image in the left eye differs slightly from that in the right eye, because the visual axes intersect the object at different angles. The nearer object, B, forms images to the right of the fovea on the retina of the right eye and to the left of the fovea on the retina of the left eye. The observer thus sees two "crossed" objects; that is, B is farther to the right as seen with the left eye than it is as seen with the right eye. The farther object, C, similarly appears as two separate objects, but they are not crossed; C as seen with the right eye is right of C as seen with the left eye. Because of these factors, the observer gets a sensation of A's being nearer than C and farther than B. Since the eyes are only some 2-1/2 inches apart, the amount of disparity between the images in the two eyes rapidly decreases with the distance of the object. The greater the disparity, the easier the judgment of distance. Beyond about a third of a mile, stereoscopic vision is of little benefit, though this distance could be extended by periscopic binocular devices that widened the separation of the visual axes. At 1000 to 1500 feet, stereopsis with naked vision may be of use under certain circumstances, but it is a less accurate cue than at shorter range.

Stereoscopes create the illusion of depth by simulating stereoscopic vision. Two photographs of the same object or area, taken from slightly different angles, are placed side by side in the stereoscope. The left eye is focused on the left-hand picture and the right eye on the right-hand picture. Thus the two eyes see slightly different aspects of the same objects in the photograph, and a true feeling of depth is created that cannot be matched by the most skillful use of perspective, haze, or any other cue on a single picture.

The second binocular cue is the muscular action required to converge the two eyes on an object. It is unrelated to stereopsis. Convergence is a weak cue, as is demonstrated by placing a prism, base out or base in, before one eye while the observer is viewing an object with both eyes. With the base out, an artificial convergence is created, and with the base in, an artificial

divergence is created. In both cases, it is noted that the observer does not appreciably change his judgment of the distance of objects.

The first of the eight monocular cues is the estimation of distance by the angle subtended by an object of known size. Thus an aircraft of known size is judged to be at a distance inversely proportional to its apparent linear dimensions (Fig. 8.22). (This method also works in reverse; that is, if distance is known, the dimensions of an object of unknown size can be estimated.) Unlike stereopsis, distance judgment on the basis of angle subtended is equally effective at all ranges.

The second monocular cue is that of aerial perspective. Objects as seen from a distance have an indistinctness of contours, a reduction in apparent color saturation (or a change or loss of color) and a change in brightness so that the contrast with the background is reduced. The changes are caused by a scattering of the light emitted by the object as the light passes along the optical path between object and eye and an addition of light to the optical path from other sources. Objects that undergo these apparent changes are judged to be at a distance.

This cue is most effective at the ranges at which the changes are most noticeable; these ranges depend on the atmospheric condition. For example, on a foggy or very hazy day, the nearest effective range for this cue is considerably shorter than the nearest effective range on a clear day. However, when extremes of atmospheric conditions occur, these atmospheric conditions must be considered in the judgment; otherwise, gross errors in distance estimation may be made. For example, it is well known that a pedestrian is more apt to be run down by an automobile he has seen on a foggy day, because his aerial perspective, uncorrected for atmospheric condition, tells him the automobile was at a greater distance. Except in foggy weather, the effective ranges for aerial perspective are in the intermediate and distant ranges (at least a thousand feet or greater).

The third monocular cue is linear perspective. There is an apparent alteration in the geometry of objects that extend to a considerable distance from the observer. For example, the rails of a railroad or the boundaries of a runway seem to converge in the distance.

The fourth monocular cue is that from lights and shadows. This cue helps disclose the position of objects relative to light sources and to other objects. It is useful at any range.

The fifth monocular cue is that of overlapping contours. It establishes definitely the order of position of objects toward the observer and so can override other cues for distance judgment. However, absolute distances cannot be estimated purely on the basis of overlapping contours; they only disclose order of position with respect to another object or objects. The cue can be used for this purpose at any range.

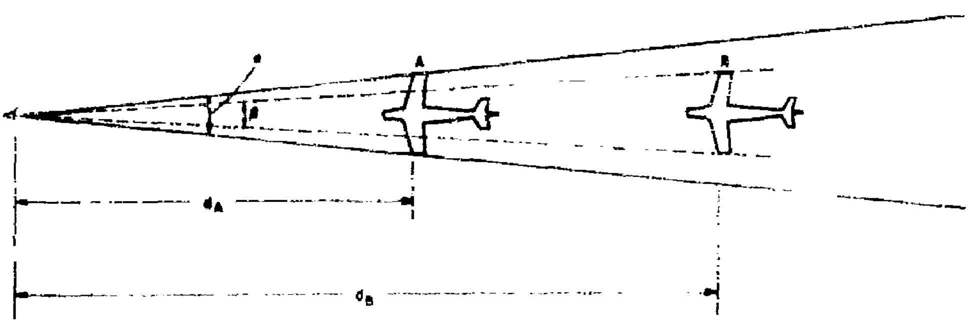


Figure 8.22 Angle Subtended at Eye (Apparent Size) as a Cue in Distance Judgment

When the aircraft moves from B to A, its apparent size increases by an amount inversely proportional to distance from eye and directly proportional to angle subtended:

$\frac{\alpha}{\beta} = \frac{d_B}{d_A} = \frac{\text{apparent size at A}}{\text{apparent size at B}}$ If the observer knows the approximate dimensions of the aircraft, he in effect solves the equation $d_A = \frac{\text{dimension of aircraft}}{\tan \alpha}$ to estimate distance at A.

The sixth monocular cue is motion parallax. This is the relative displacement of objects as seen when the observer is moving. When the observer is riding in a plane, near objects appear to be moving past in the opposite direction with respect to the most distant object fixated upon. When fixation is upon near objects, distant objects tend to move in the same direction as the observer. The rates of apparent movement are inversely proportional to the distance from the observer. Objects near the plane appear to move most rapidly while distant objects appear to be almost stationary. Then when motion parallax is used in judging the distance of objects from a moving vehicle, those objects that appear to be moving rapidly are judged to be near, while those moving slowly are judged to be distant. A stationary observer may use motion parallax in judging distance by moving the head from side to side. This seems to distinguish the planes of objects that lie in the same direction. With motion parallax a judgment of depth can be obtained as with stereopsis. The difference here is that one image is compared with the memory image of a preceding impression instead of with the simultaneous image in the other eye.[8-19] Motion parallax is useful for all ranges.

The seventh monocular cue is accommodation. This is a very weak cue, useful chiefly at short ranges. For example, a reduction in accommodation of 1/2 diopter at 33 cm changes the accommodation to 40 cm. A reduction of 1/2 diopter at 200 cm changes accommodation to infinity. In other words, accommodatively, a change from 33 to 40 cm is the same as a change from 200 cm to infinity. Therefore, accommodation cannot be very sensitive to changes at ranges beyond a few feet.

The eighth monocular cue is association. This cue is not often of decisive value, but occasionally it indicates distance better than any other cue available. Association is illustrated by the following example. Five miles out on a low altitude approach to an air base, a pilot sees another aircraft nearly directly ahead. He does not know the type of aircraft; therefore he does not know the size, and the subtended angle cannot indicate the distance. But he notices that the aircraft is making turns as it would for the traffic pattern. Therefore, he is able to associate the distance with that to the airport. This cue, on the occasions when it is present, may operate at any range and may, in fact, interact with all of the preceding cues except, possibly, binocular disparity.

In addition to the above cues, a misleading cue to distance is furnished by some types of optical aids. This false cue is "instrument minification." Objects seen through a telescope of one-to-one magnification -- a telescope designed to give no change in size -- appear to be smaller and more distant than when seen with unaided vision. The cause of this phenomenon is unknown. It was formerly thought to be due to restriction of the field by the housing of the telescope, but this has been found to be an incorrect explanation. Curvature of the field produced by the optics in the telescope is now considered the probable cause. This misleading cue is a serious problem in designing periscopes for piloting aircraft.

Measuring Distance Judgment. Most laboratory tests of distance judgment are tests of the ability to judge relative distance, and they are set up so that the observer must make his judgments only on the bases of stereoscopic vision and muscular adjustments for accommodation and convergence. That is, the test objects are chosen and presented in such a way that relative size is meaningless; and other cues, such as light, shade, and relative motion, are absent. For example, a movable line, disk, or similar object may be placed closer or farther away than a fixed object. The movable object is then moved until the observer judges that it is exactly aligned with the fixed object, or he may be asked simply to make a judgment as to whether it is closer or farther.

Distance judgment is often expressed as the difference in parallax corresponding to the minimum distance two objects can be displaced along the line of sight and still be recognized as being at different distances. To understand what this means, refer to Figure 8.23. A and B are two points at distances $y - x$ and y from the observer. The eyes are a distance a apart. The distance x between the points is small compared with the distance y from observer to point B. Angle α is the parallax -- the angle of divergence -- between rays from point A to the two eyes, and angle β is the parallax for B. In radians, $\alpha = a/(y - x)$, $\beta = a/y$, and the difference between the two, η, is found by $\eta = a/(y - x) - a/y = ax/(y^2 - xy)$. Since x is small, η is approximately equal to ax/y^2 radians, or $206{,}000\ ax/y^2$ seconds of a degree.

Laboratory tests show that the eyes can make very fine discriminations in relative depth. Values as low as two seconds for η are not uncommon. Judging absolute depth -- the number of inches, feet, yards, or miles an object is from the observer -- is much less accurate, and it depends on so many cues that it does not lend itself to laboratory analysis. While distance judgment probably improves with experience, the naked eye does not approach even an old-fashioned stadiametric rangefinder in accuracy.

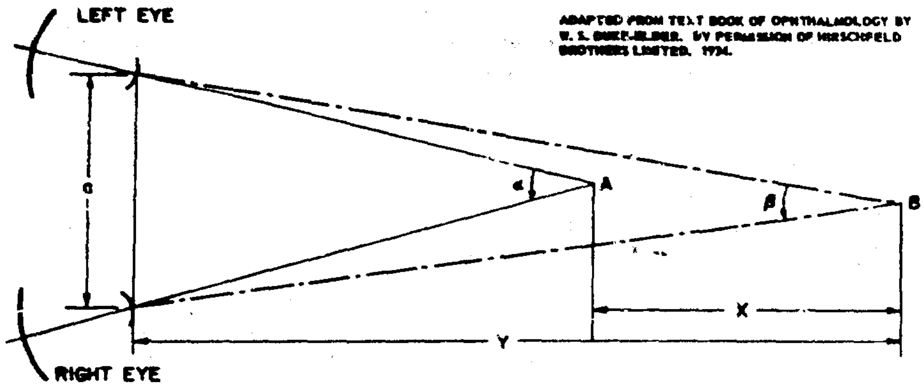


Figure 8.23 Distance Judgment is Often Expressed as the Difference in Parallax Corresponding to the Minimum Distance Two Objects Can Be Displaced Along the Line of Sight and Still be Recognized as Being at Different Distances. (after Duke-Elder[8-19])

Form Discrimination. Form discrimination, as used here, is the ability to distinguish objects on the basis of shape. It requires visual acuity plus experience in recognizing and describing the shape; it is in large part on the perception level of response. For three-dimensional shapes, depth discrimination is also a factor. There are, of course, any number of forms in both two and three dimensions. The ability to discriminate any one depends on whether it is viewed by itself or with similar or dissimilar forms. It also depends on the amount of illumination, the length of time the form is viewed, and other conventional factors. For all these reasons, form discrimination cannot be analyzed as exactly in the laboratory as visual acuity or the stereoscopic aspects of depth discrimination.

In experiments with form discrimination, the ability to recognize a form is determined under carefully controlled conditions. Typically, either the speed of recognition is measured, or the probability of correct recognition is determined on the basis of the number of right and wrong judgments.

However, the term "recognize" means different things in different situations. In some situations, it means the ability to pick out a particular form from a number of alternatives -- a square, for example, from a number of rectangles. Similarly, the observer may be asked to sort a group of forms into categories such as rectangular, rounded, and triangular. In these cases, if the alternative forms are unlike or the categories are well differentiated, recognition will be rapid and the probability of correct recognition will be high.

In other situations, "recognize" means the ability to detect whether a form is present or absent. Not only are illumination and contrast involved in this type of visual performance, but such variables as background clutter and familiarity of the forms are important. Correct recognition, therefore, depends upon particular details of the experimental situation. This kind of test is thus useful chiefly in measuring a person's ability to discriminate forms that are to be used in some specific practical situation.

Whatever the method of experimentation, the practical goal is to isolate the characteristics of forms that make them easy to recognize. These characteristics can then be used to design knobs on instrument panels so that the operator can pick out the right one quickly, to design easily recognizable runway markers on airfields, and for many other purposes. Unfortunately, there appears to be little connection between the physical form and the ability to discriminate form, nor can form discrimination be measured in terms of a standard, in the way visual acuity, for example, is measured. Psychologists have tried varying total area, the shape of the perimeter, and other characteristics of form, but only limited success has been achieved in making the forms easier to recognize.

Movement Discrimination. Movement discrimination may be described as the ability of the eye to detect a change in position of an object appearing in the visual field. Two types of movement may be observed -- real and apparent.

Real Movement. Real movement occurs when a physical object moves in space relative to the location of the eye. A similar situation occurs when the eye moves relative to a stationary object. In either case, the image of the object passes from one group of retinal elements to the next and the speed at which this must occur to be discriminated is the threshold for movement.

An aircraft a long way off has such a low angular velocity with respect to our eyes that we have no direct perception of motion. We know that it is moving only because its position or apparent size changes over an interval of time. As the aircraft comes closer, however, this more or less intellectual appreciation of movement changes to a direct sensation of motion. Thus, there are two stages to our perception of real movement: the indirect, for slow or distance objects, arising second-hand from our perception of a series of changes in size or position; and the direct, which occurs when these changes in position merge into a single sensation of motion.

The perception of movement is caused by (1) the successive location of the image at different receptors of the retina (i.e., movement in relation to the periphery of the visual field) and (2) the change in the location of the object with respect to other objects in the field of vision. Perception of movement is aided by movement of eye muscles and head to keep a moving object in focus, but these movements are not essential to the perception. When the object is moving rapidly, the successive images on the retina or in relation to fixed objects are synthesized in the brain into a single, direct perception of movement.

Movement in relation to fixed objects is perceived with greater ease than movement in an otherwise empty visual field. That is, we perceive that an object has changed location much more quickly if it is moving past a fixed object, and we get a direct perception of movement at much lower velocities.

Movement discrimination can be measured either in terms of the angular velocity of an object or its angular distance of displacement. Often, the threshold -- the lowest angular velocity at which an object will still be judged as moving -- is determined for a moving test object of rectangular shape or a gap in a rotated circle.

Apparent Movement. In the case of apparent movement, a perception of movement is created even though there are no moving objects in the visual field. Apparent movement is illusory in nature and is based on imperfect perception of stimulation from the external world. However, enough is known of the clues for these false perceptions to permit measurement of apparent movement in terms of physical characteristics of the stimuli.

One kind of apparent motion occurs when the head, eyes, or body is moved. Usually we recognize this as apparent motion; the images moving across our receptors give no sensation of motion, because (1) the observer knows that the objects are stationary in relation to himself, and (2) his attention is usually fixed on one object, to the psychological exclusion of the objects in apparent motion relative to it. However, after a rapid spin, loop, or steep bank, we have a direct perception that the stationary world around us is moving rapidly in the opposite direction to our motion. This kind of apparent motion is of serious concern to pilots trying to extricate themselves from unusual attitudes. It can be overcome to some extent by training; after a spin, one can stop the apparent motion sooner by fixating a stationary object on the ground.

Stroboscopic movement occurs when a series of lights or a series of pictures of successive positions are flashed on successively, thus stimulating different portions of the retina, as in real movement. The latter procedure is, of course, the basis of the movies. In somewhat similar fashion, certain geometrical designs, when rotated, give an illusion of radial or vertical motion. A familiar example is the rotating barber's pole.

When one or two lights are seen against a dark background, the observer has no pattern of reference. Various types of apparent motion may set in, depending on the individual. For example, if

the upper of two lights is swinging and the lower is stationary, the observer, if he has a pendulum in mind, may see the lower as swinging and the upper as stationary. A single light, fixated at night, may suddenly appear to leap or swing in the field of vision. This illusion is especially likely to occur if the observer is in a moving aircraft. Such problems become serious when a pilot is fixating another aircraft's tail light while flying formation at night and in other situations that come about in night flying. We shall discuss them further in later sections of this report.

Apparent motion can be measured under some circumstances by comparison with a standard. That is, an object that is actually moving at a known velocity may be presented along with the apparently moving object, and the observer reports which seems to be moving faster; or the velocity of the standard is adjusted until judged equal to the apparent speed of the other object. The apparent velocity can then be related to the physical characteristics of the object.

Temporal Discriminations

The growth and decay of visual sensations are by no means instantaneous. Periods of 0.05 to 0.2 second have been noted between a change in the stimulus and the resulting sensation change. These latent periods depend primarily on the color and intensity of the stimulus. They are the basis for several kinds of visual performance, but only one, flicker discrimination, will be considered here.

Flicker Discrimination. Flicker, an oscillation of the apparent brightness of a light source, can be created by fluctuation of the intensity of the source or by chopping a beam of light with a shutter. Under the proper conditions, the pulses of light reaching the eye can be fused together to produce the sensation of a steady light. In other words, the sensation of one pulse has not decayed detectably before the next pulse occurs. The frequency at which successive pulses can no longer be discriminated is the threshold value; it is called the critical flicker frequency (CFF).

In practical applications, a knowledge of flicker discrimination is important both when "steady" lights are to be produced from oscillating current sources and when flicker is to be intentionally designed into a system, as in warning lights and flashing signals. It is also important to be aware of some complex adverse effects which coarse flicker may have on human performance. For example, coarse flicker produced by the rotor under certain conditions has been reported to cause symptoms of extreme fatigue and even dizziness and nausea in helicopter pilots. Coarse flicker is also known to depress the CFF so that care should be taken in using flashing light signals under conditions of coarse flicker in the environment.

INTERACTION OF VISUAL VARIABLES

In the preceding pages, almost a dozen different kinds of visual performance were described. For each there was some particular visual capacity and particular stimulus characteristic that could be related to the kind of discrimination being made. For instance, visual acuity performance was related to the broader capacity for making spatial discriminations and also to the particular stimulus characteristic, visual angle. This kind of visual performance (i.e., visual acuity) was also selected as being so basic to general visual efficiency that it constitutes one of our five basic curves. A number of the associated variables which will also influence the values obtained for each kind of visual performance unless they are carefully controlled during measurements have also been mentioned. These variables are summed up in Table 8.1. Note that there is considerable interaction between the variables that determine visual performance. These interactions are so important that, after you have reviewed Table 8.1 and the five basic curves generalized from the mass of available data, we suggest that you study the pages which follow. There you will find basic information about vision hung on a framework of practical visual problems.

VISUAL PERFORMANCE PROBLEMS

Each of the simple problems that follows has been chosen to show how some physical change by an engineer or designer might affect the visual performance of the human operator. When an engineer designs or redesigns an airplane or any piece of equipment in it, or any ground aid for pilots or navigators, he is interested in how it will affect the ability of pilot and crew to see properly. By "see properly," we mean see any dial, light, control, or chart inside the aircraft and any obstruction,

Table 8.1 Variables That Must be Kept Constant or Carefully Controlled When Measuring Some of the Principal Kinds of Visual Performance

Type of Visual Performance	Variables to Be Controlled												
	Level of Illumination	Region of Retina Stimulated	Stimulus Size	Stimulus Color	Contrast Between Test Object and Background	Adaptive State of the Eye	Duration of Exposure	Distance at Which Measured	Number of Cues Available	Movement	Other Objects in Field	Monocular vs. Binocular	Stimulus Shape
Visual Acuity	X	X	(MV)*	X	X	X	X	X		X			X
Depth Discrimination	X		X	X	X	X	X	X	X	X	X	X	
Movement Discrimination	X	X	X	X	X	X	X	X		(MV)*	X		X
Flicker Discrimination	X	X	X	X	X	X	X						
Brightness Discrimination	X	X	X	X	(MV)*	X	X			X		X	X
Brightness Sensitivity		X	X	X	(MV)*	X	X			X			X
Color Discrimination	X	X	X	(MV)*	X	X	X	X	X		X		

*Variable being measured

other aircraft, navigational, or landing aid outside the aircraft, and see it quickly and clearly enough to operate the plane safely and effectively. These statements are obvious for equipment that is designed to be seen -- for dials, oscilloscopes, lights, runway markers, and the like. They apply almost equally, however, to many other aspects of aircraft design. A new communications device, for example, may obstruct the view, or may mean a new dial or knob that will be hard to discriminate from other knobs or dials. A radome tends to obstruct the pilot's over-the-nose vision. This can be of serious concern in, for example, reconnaissance aircraft. A new aerodynamic configuration can alter the shape and size of the windshield, change the landing attitude, or change the pilot's position with respect to instruments and windshield.

When the effects of such changes on vision are not predicted, they may reduce the effectiveness of the weapon system, contribute to accidents, and an expensive change or retrofit may be necessary after the airplane is in production. Such has occurred in the past. Curves 1 through 5 and other data on vision give the engineer a scientific basis for predicting how the changes he makes will affect pilot's and crew's vision. They also enable him to make further changes that will undo any ill effects his first change has on vision (assuming the first change is necessary). They enable him to predict the most effective ways of arranging and designing equipment for efficient visual performance.

These predictions will not always be completely accurate, of course, but they will almost always be much more accurate than guesswork -- even guesswork based on pilots' opinions (because pilots tend to like what they are accustomed to rather than what will ensure best visual performance).

Some of the variables an engineer manipulates or can manipulate in the course of designing or redesigning the parts of an aircraft that influence visual performance are:

A. Position
B. Spectral Composition
C. Intensity
D. Duration
E. Visual Angle Subtended
F. Spatial Arrangement

To a certain degree, these physical variables are related to the visual (psychological) variables we have mentioned previously. The engineer's physical variables constitute what is meant by stimulus characteristics. The table below may prove helpful as a summary if we remember that all of the variables interact in complex fashion:

Visual Variables (Psychological)		Engineering Variables (Physical)
Variations of Image Position on Retina	- Rod-cone anatomical plot (Basic curve 1) See Fig. 8.24	A. Position
Light Discriminations	Spectral sensitivity (Basic curve 2)	B. Spectral Composition
	Brightness sensitivity (Basic curve 3)	C. Intensity
	Contrast sensitivity (Basic curve 4)	
	Color sensitivity	
Spatial Discriminations	Visual acuity (Basic curve 5)	E. Visual Angle
	Depth discrimination	
	Form discrimination	F. Spatial Arrangement
	Movement discrimination	
Temporal Discriminations	- Flicker sensitivity	D. Duration

We will give examples to show how an engineer, by manipulating either position, spectral composition, intensity, duration, visual angle, or spatial arrangement, may affect the vision of aircraft personnel. We will show how he can deliberately manipulate the other variables to improve vision. The examples will be presented in this way:

First, it will be assumed that for some reason an engineer wants to change the position, spectral composition, intensity, or some other characteristic of some device inside or outside the aircraft; e.g., we will suppose that the engineer wants to change the position of a not very essential warning light -- to move it to the far side of the cockpit to make more room on the instrument panel.

Next, the effect of this change will be examined in the light of the five basic curves of visual performance; e.g., "If warning light is moved from central vision to a point 40 degrees out in the field of vision, curve 4 shows that ability of eye to discriminate detail is reduced."

Finally, we will show how the engineer might make a second change to correct a bad situation created by his first change; e.g., "Curve 3 shows that if the intensity of the light is increased, the effect of moving it to the periphery of the field of vision will be partly compensated." Additional curves and data will be introduced within each example as they apply.

Several words of explanation and caution are indicated at this point. The examples in this chapter may seem rather extreme and artificial. The choices were made with malice aforethought -- to show how to apply visual data to the design of airplanes and associated equipment. Since the method employed here requires the use of simple examples, it would be wise to keep in mind that any real situation is highly complex. Yes, you can move a warning light to the far side of the cockpit. Whether or not Pilot A sees it when he is flying a mission depends not only on the characteristics of the eye, but also on what else the pilot is doing at the moment the light flashes on. It also depends on such things as how long he has been flying, and, perhaps, even how old he is. Another pilot in the same situation might see the warning light when Pilot A does not. Because of the multitude of such influencing factors in any real situation, the luminance, size, and other characteristics affecting vision must be well above the threshold values presented in this chapter. The addition of a safety factor should be kept in mind at all times -- as it is in any engineering calculations. These examples are for illustrative purposes only. The practical problems that arise in designing and flying aircraft are discussed in later chapters of this report.

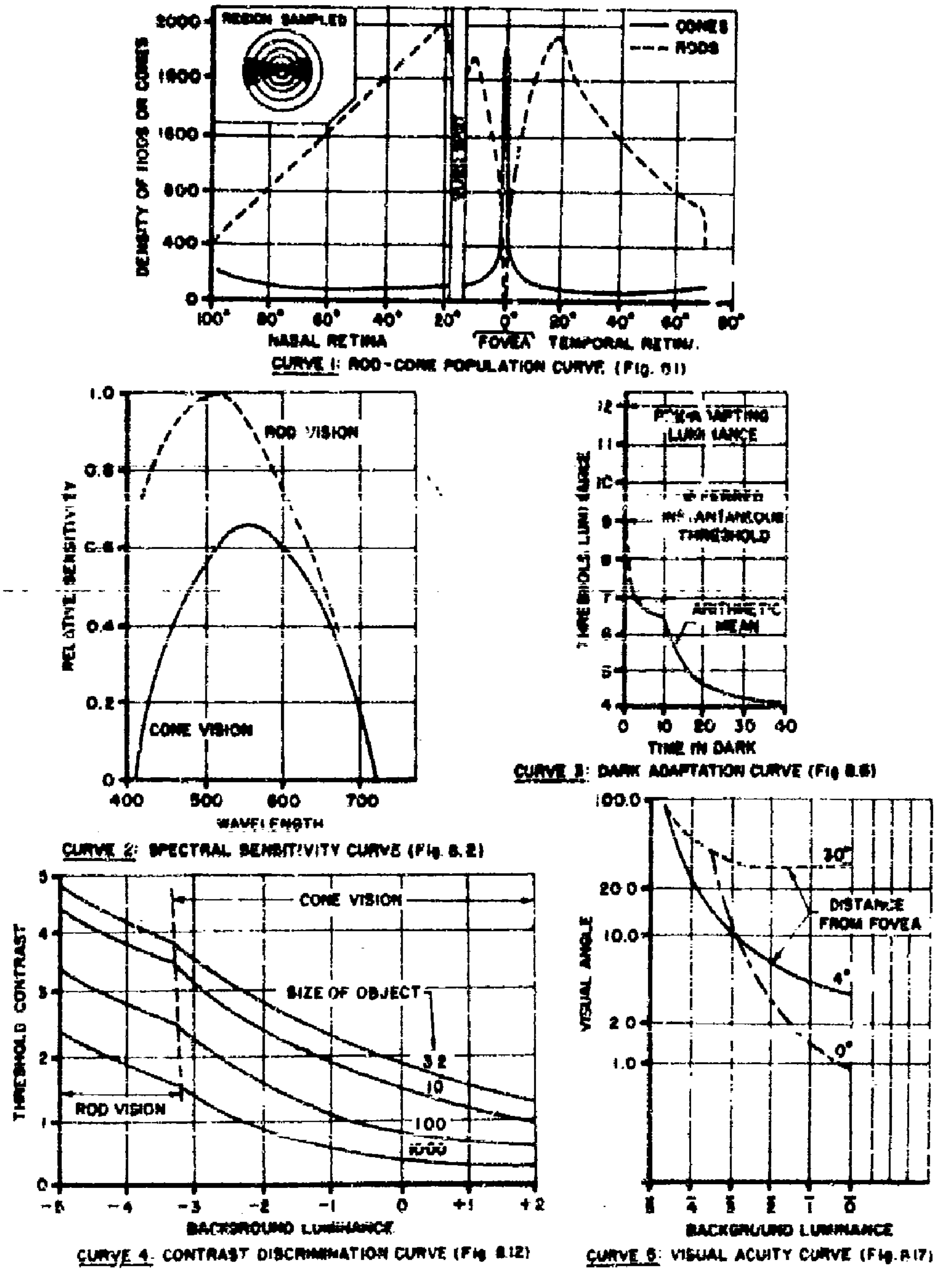


Figure 8.24 The Five Basic Curves

Example A: Changing Position in Relation to Line of Sight

To illustrate the visual effects of changing the position of a stimulus in relation to the line of sight, we will consider in more detail the not-very-essential warning signal mentioned earlier.

Engineering Change. Because the instrument panel is too crowded, the engineer plans to move a warning signal to the far side of the cockpit. The signal warns of a minor kind of engine malfunction; it consists of a small, translucent red circle that is replaced by a rectangle when the malfunction occurs. Assuming that the pilot is looking straight ahead -- at his instrument panel or out over the nose -- the engineer calculates that the signal will now be 40 degrees from the pilot's line of sight; its image will thus fall on the retina 40 degrees away from the fovea (i.e., from central vision). The engineer hopes that the pilot will still catch the signal "out of the corner of his eye."

Effects of Change on Visual Performance

Curves 1 through 5 (Fig. 8.24) help the engineer predict whether his hope is justified. He finds:

From curve 1, that rods and cones will be stimulated in a ratio of 16 to 1 by a signal 40 degrees from the line of sight.

From curve 2, that although rods and cones are about equally sensitive to the red (long-wave) end of the spectrum, sensitivity is low for both. Furthermore, the response of the rods is achromatic; the red signal will appear colorless.

From curve 3, that the pilot may not be able to see the signal for some time if it is dim compared to the illumination his eyes have just been exposed to -- a bright sky, for example. However, curve 3 shows dark adaptation for the eye as a whole. What about the peripheral area we are concerned with? Figure 8.11 includes adaptation curves for various distances from the fovea. While none of these are anywhere near as far out as the signal we are considering, they do indicate that dark adaptation is faster and more effective as the angle from the line of sight increases. Nevertheless, a certain minimum time is required for dark adaptation no matter where an object is located with respect to line of sight.

From curve 4, it can be inferred that the rod receptors that will be used to see the warning light will discriminate brightness differences poorly. (The curve indicates that the smaller contrasts are discriminated with cone vision.)

From curve 5, and other data, that visual acuity will be extremely poor in this region of the retina under both daylight and night-lighting conditions.*

From the foregoing, it can be seen that a warning signal designed to be seen with central vision on the instrument panel would probably be seen less frequently if it were moved without change 40 degrees into the peripheral field. Let us now see what the engineer can do to correct the situation

Further Engineering Changes to Improve Visual Performance

Earlier in this chapter, we listed six "engineering variables" -- physical characteristics that the engineer can manipulate to change visual performance. Let us consider whether the engineer can make the warning signal visible by altering each of these characteristics in turn.

A. Position. Since his troubles are due to his having moved the signal in the first place, the simplest solution is to move it back to the instrument panel. If this is not possible, he may still find a place for the signal closer than 40 degrees to the line of sight. In this case, he repeats the procedures outlined above for predicting the effects of this new change in position on visual performance.

*For the complete picture on visual acuity, other curves would have to be examined: curves showing acuity vs. retinal position (such as Fig. 8.25), acuity vs. wave length, and acuity vs. luminance values higher than those in curve 5. However, since this example is purely for illustration, you can assume that acuity is poorer for 40 degrees and red light than it is for the 30° curve in curve 5, Figure 8.24, and that it does not improve with luminance levels above 0 log units.

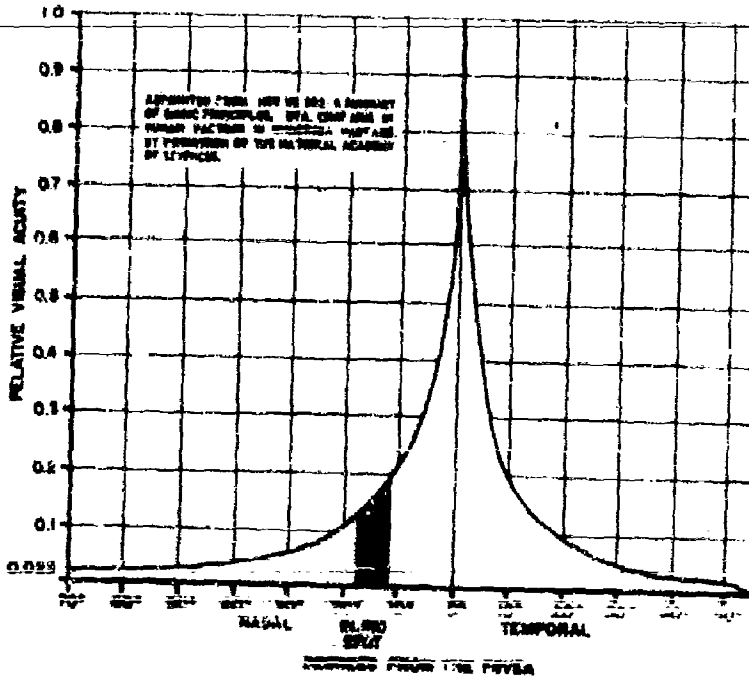


Figure 8.25. Curve of Daylight Visual Acuity for Different Parts of the Eye (from Chapanis[8-26]) (data from Wertheim[8-30])

B. Spectral composition. By changing the color of the signal from red to green, he will use a portion of the visible spectrum to which the rods are much more sensitive (see curve 2, Fig. 8.24). Changing to white would have a similar effect. (*However, the engineer would also consider that red is the traditional color for warnings, and that spectral composition changes with the type of illumination -- see Color Specification, Chapter 2.*)

C. Intensity of stimulus. Provide the best possible brightness contrast between signal and background. The area immediately surrounding the signal should be black rather than gray or white. Discrimination of brightness differences is poor for the rods in this area of the retina.

D. Duration of stimulus and adaptation time. The engineer has no control over these items in this case. The signal will be on while the malfunction lasts -- no more, no less. And since the pilot does not know ahead of time when he will have to see the signal, no provision can be made for dark-adaptation in advance. Instead, the engineer must provide a light bright enough so that the pilot can see it with no adaptation. How bright should it be? Curve 2 (Fig. 8.24) shows that when the eye has been exposed to a high level of illumination -- 12 log units $\mu\mu L$, or 10^3 mL -- it can see, immediately thereafter, much lower levels of luminance -- 9 log units, or 1 mL (i.e., with no adaptation at all). Since 10^3 mL is close to the brightest conditions the pilot is likely to encounter -- the luminance of cloud tops in bright sunlight (see Fig. 2.12, Chapter 2) -- a signal of 1 mL will be bright enough in theory (assuming good contrast with the background). However, since the periphery of the retina is to be used, the signal should be made several times brighter than that. A means can be provided to reduce the brightness of the signal at night.

E. Visual angle subtended (size and distance of signal). An effective way to increase the visibility of the signal is to increase its size. More receptors (rods and cones) will thus be stimulated and the chances of discriminating a change in signal shape will be increased.

Figure 8.25 shows that visual acuity drops off very rapidly at first with distance from the fovea, and continues dropping more slowly toward the periphery.[8-27] Acuity at 5 degrees to the right or left of the line of sight is just half as good as it is at the fovea. At 40 to 50 degrees, it is only 1/20 as good.

Thus, a signal at 40 degrees will have to subtend 20 times as big a visual angle as one on the instrument panel to be seen with the same acuity; it will have to be 20 times as big (in linear dimensions), plus an additional amount to make up for increased distance from the pilot.

F. Shape. It will be remembered that the warning signal is a circle that changes to a rectangle when malfunction occurs. Can the engineer increase the effectiveness of the signal by changing its shape? Earlier, we pointed out that form discrimination depends on a number of variables and is difficult to analyze. However, one laboratory experiment fits the warning signal situation neatly:

In an experiment[8-31] on peripheral form discrimination, the apparatus included a perimeter (see Fig. 6.6, Chapter 6) with a red fixation point. Background was provided for stimuli and stimulus carrier. Stimuli were translucent surfaces in the forms of a circle, triangle, diamond, hexagon, rectangle, and square, each having an area of 10 cm^2. The brightness of each stimulus was 244 mL. Distance from eye to stimulus was 60 cm. Three subjects were dark-adapted for 45 minutes and then made observations for one hour, using both eyes. They were given a "ready" signal before the forms were shown. They were asked to name the forms as they were presented. The forms were presented in chance pairs -- i.e., sometimes identical forms and sometimes different forms were presented. Both forms of each pair were shown at the same angle to left or right of the line of sight, one of the pair in the upper quadrant of the visual field and one in the lower. Discrimination was tested at 10-degree intervals; each pair of forms was presented (1) three times at each 10-degree interval, beginning at 20 degrees from the center and proceeding toward the periphery, (2) three times at each 10-degree interval from the periphery inward, (3) two times out, as in (1), and (4) two times in, as in (2). The outer limit of the field was taken as the 10-degree interval at which subjects reported they could discriminate nothing except spots of light.

There were fewer correct discriminations as extension toward the periphery was increased. Percent correct also varied as a function of the geometric form used as the stimulus; relative rank of the six forms in the whole field investigated, in terms of percent accuracy, was: triangle, 88%; diamond, 73%; square, 66%; rectangle, 57%; circle, 57%; hexagon, 40%.

This experiment indicates (1) that changing the shape of the signal to a triangle or diamond during the "on" period would make it easier to recognize and (2) that at 40 degrees from the line of sight, a warning expressed only as a change of shape in the signaling device will go unheeded much of the time; a change in brightness or some other characteristic is required.

Conclusion. The foregoing discussion does not of course exhaust the possibilities. The engineer could, for example, investigate the effects of using a flashing light or a buzzer or bell instead of a steady visual signal. Furthermore, in situations where visual performance was critical, a more detailed analysis of more visual data would be necessary.

As a final step, the engineer could have an actual warning signal device made and try it out under conditions simulating those of an airplane in flight as closely as possible, using enough subjects and enough trials so that he could get an indication of its reliability.

Example B: Changing Spectral Composition (Color)

Engineering Change. Runway lights are usually white, taxi lights blue, and edge and obstruction lights red. Suppose the blue has a wave length of 476 mμ and the red of 675. If the engineer decides to change the runway lights from white to an "orange" of wave length 650, what will happen? Pilot may hit an obstruction, since red and orange lights are often confused.

Effects of Change on Visual Performance

If white is changed to orange, as in this situation, the engineer can predict:

From curve 1 (Fig. 8.24), that since the pilot may fixate the light directly -- with foveal vision -- the image will fall in the region of maximum cone density on the retina. Thus, the pilot will be able to use his ability to discriminate color to the fullest.

From curve 2 (Fig. 8.24), that in the original situation, the red was less bright than the blue (assuming that the energy of the red was not stepped up to compensate for lower eye sensitivity to

red). Other visual data can be cited to show that both were less bright than the white. There was thus a brightness difference as well as color coding. Now, with the change from white to orange, the runway lights will not be much different in brightness from the red obstruction lights, and they will not be picked up at any greater distance. The chances are thus increased that the runway and obstruction will be confused.

From curve 3 (Fig. 8.24), that if the intensity of the lights is high enough, the pilot will see them quickly -- with no adaptation time -- when he gets reasonably close (that is, even if he is not dark-adapted, he will see them when the illuminance falling on his eyes is equivalent to a luminance of about 8 log units $\mu\mu$L, or about 0.1 mL).

From curve 4 (Fig. 8.24), that contrast is probably sufficient, since we have the source against a dark background.

Curve 5 (Fig. 8.24), visual acuity, probably does not apply, since at a distance, lights of standard size will be, in effect, point sources. That is, ability to discriminate them is a function of intensity rather than visual angle subtended.

Further Engineering Changes to Improve Visual Performance. It can be seen from the foregoing that, if orange must be used for runway lights, it may be confused with red. If orange is used, the engineer can manipulate other variables, as he did in the previous example. Let us consider three of these variables: intensity, visual angle subtended, and spatial arrangement:

Intensity. If the intensity of the orange runway lights is increased, so that they are appreciably brighter than the red obstruction lights, the difference in brightness will again help the pilot tell the two apart. Whether an increase in intensity will make the colors easier to discriminate is another question. To answer it, we will introduce some new data:

Figure 8.26 shows that yellow lights require the greatest intensity to be identified correctly 90 percent of the time.[8-8] At low background illuminances (which may be assumed for runway lights), white can be identified at the lowest intensities, and red is nearly as good. However, it can be inferred from curve 2 (Fig. 8.24) that the threshold intensity for detecting a light (as against discriminating it from lights of other colors) is higher for red than for lights of other colors. It is important to note that the data in Figure 8.26 applies only when the observer knows the location of the signal. When the observer knows only the general direction of the signal, the threshold values should be doubled.

In the study[8-8] that produced the data for Figure 8.26, it was found that red is rarely confused with green or vice versa, but blue light is frequently confused with green, and yellow with red. It would be expected that orange would be even easier to confuse with red. This is borne out by Figure 8.16.[8-4] In the red portion of the spectrum, so great a difference in wave length is required for two color samples to be distinguished that the threshold difference does not even show on the graph. Other studies have revealed that reds must be 20 millimicrons apart before the eye recognizes that they are of different hues; 20 mμ is almost the difference between the orange of 650 mμ and the red of 675 mμ that are being considered in this example. On the other hand, the blue of 476 mμ could be distinguished from a blue of just a few millimicrons higher or lower; it could easily be distinguished from an orange or red some 200 mμ away. It must be remembered that the results for Figure 8.16 were obtained under ideal conditions; the color samples were presented side by side close to the observer and under good illumination. Where the colored lights are some distance apart, as on an airfield, and where atmospheric conditions will usually intervene

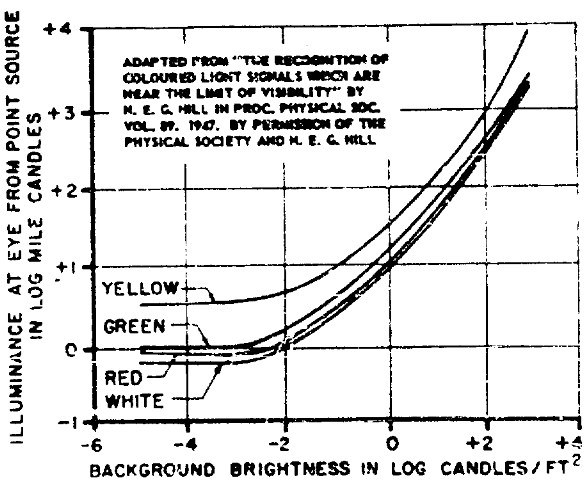


Figure 8.26 Illuminance from Point Sources of Light Required to Identify Color Correctly 90 Percent of the Time, Plotted for Four Colors as Function of Background Brightness (after Hill[8-8])

to some extent, the differences in mμ would have to be greater than those in Figure 8.16 to be distinguished as separate hues.

Visual Angle Subtended. The engineer can increase the size of all three lights (taxi, runway, and obstruction) so that instead of being, in effect, point sources, they subtend an appreciable angle at the pilot's eye (e.g., translucent panels). This will increase their effective brightness, and the distance at which they can be seen, as is shown by the following data:

The graph in Figure 8.27 shows that large areas are much more visible than small areas of equal luminance. If the lumens emitted per unit area (i.e., the luminance) are held constant, the target with the larger area will obviously emit the greater total number of lumens and thus deposit the greater number of lumens at the eye.[8-25] It is interesting to note that the curve in Figure 8.27 has the same shape and shows somewhat the same values as the 0-degree and 4-degree curves in curve 5, Figure 8.24, which show visual acuity [illegible] luminance of source.

Another study was made of the color confusions of normal observers comparing small paired circular stimuli subtending 2, 3, 5, and 7 minutes of visual angle. The results showed that confusions were reduced as the size of the stimulus was increased from 2 to 7 minutes.[8-25]

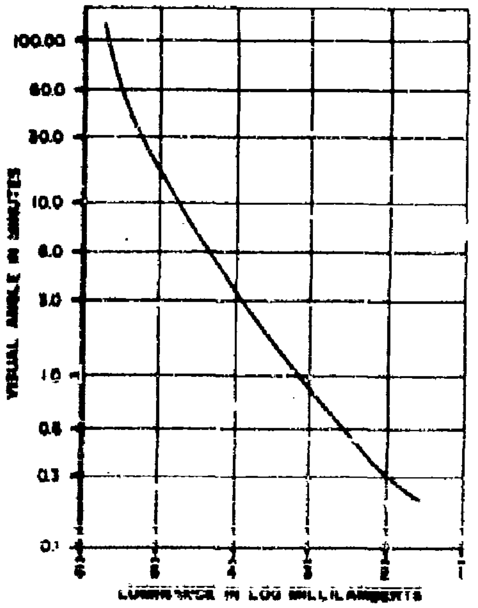


Figure 8.27 Minimum Visual Angle a Light Source Can Subtend at the Eye and Still be Seen, Plotted as a Function of Luminance of the Source (data from Lash & Prideaux[8-25])

Spatial Arrangement. The engineer can help the pilot distinguish runway and obstruction lights by arranging them in distinctive patterns and by keeping the two types as far apart as possible.

Conclusion. The discussion in the foregoing paragraphs shows that the engineer would be unwise to place orange lights in the same area as red lights when it is important that the two be distinguished from each other (i.e., red means obstruction and must be interpreted as such); further, he should not choose two colors that are close together in dominant wave length. It further shows that if the colors of two kinds of lights might be confused for any reason, the engineer can correct the situation as follows: (1) He can improve the chances that the colors will be recognized by increasing the intensity or size of the lights. (2) He can design the lights so that they can be distinguished on the basis of arrangement, relative intensity, or some other characteristic besides color.

Example C: Changing Luminance

Engineering Change. In a day interceptor, the pilot has the job of scanning the day sky and the next moment detecting pips on a radarscope. The scope, because it is directly in front of him, has to be small. The scope face is dimly illuminated with yellow-green light, and pips are green. There are complaints that the pilot requires too much time to adapt to scope-face illumination after scanning the bright day sky. So, the design engineer steps up the illumination of the scope face. What happens?

Effects of Change on Visual Performance

As in Examples A and B, the engineer can predict the results of his change from curves 1 through 5 (Fig. 8.24). If he increases the luminance of the scope face, he finds:

From curve 1, that since the pilot will be using central (foveal) vision, he will be using only cone receptors to fixate the pips on the scope face.

From curve 2, that raising intensity is a better approach to the problem than changing color, since the cones are already most sensitive in the yellow-green portion of the spectrum.

From curve 3, that less time will be required for adapting to this raised level of illumination, but --

From curve 4, that the pip will be detected more quickly with a low contrast at high luminance values than it would with the same contrast at low luminance values. By calculating visual angle subtended by the smallest target pip and using the actual luminance values of pip and background, he could use curve 4 to find whether the pip would be detected at the contrasts involved. However, a "safety factor" should be incorporated to make certain that contrast will be sufficient, even if the pilot is not fully adapted to scope illumination.

From curve 5, that acuity will probably be reduced as a function of the decrease in contrast that will occur when scope-face brightness is increased toward pip brightness.

Actually, curve 5 shows that acuity decreases as a function of decreased background luminance. However, this curve is based on data for a dark object against a light background; as background luminance is decreased, contrast between object and background is also decreased, and it is obvious that the decrease in acuity is due to this change in contrast rather than to the absolute change in background luminance. In the case of a bright radar pip against a dim background, increasing the luminance of the background reduces contrast, and therefore acuity. (If the engineer requires exact information on visual acuity for the radarscope, he should consult data that give acuity as a function of contrast for the actual luminance values involved and for the yellow-green portion of the spectrum.)

Further Engineering Changes to Improve Visual Performance

From the foregoing, it can be seen that if the luminance of the scope face is increased, the engineer will probably have to manipulate other variables so that the pilot can detect target pips and locate them accurately on the scope face. If he cannot change the position of the scope, so that its size can be increased without pushing other instruments out further, he might alter, for example, spectral composition, luminance of pip, or shape of pip.

Spectral Composition. We have already seen that the eye is most sensitive to the yellow-green illumination of the scope face. However, the engineer might improve contrast by changing the wave length of the phosphor or the scope illumination or by changing the filter (if there is one) for optimum contrast. In other words, to make up for the decrease in brightness (achromatic) contrast, increase color (chromatic) contrast. Perhaps a change to yellow phosphor would be best, since visual acuity is best for yellow. Consider the following data:

One study[8-20] showed that hue differences generally have less effect on visual acuity than achromatic brightness contrast when both are present. That is, a difference in brightness is better than a difference in color where the problem is to discriminate small objects like radar pips. If brightness contrast is reduced, however, hue differences may increase acuity, provided that the introduction of hue difference does not further reduce brightness contrast.

Luminance. In view of the foregoing, the engineer might better increase brightness contrast by brightening the pip, so that it again stands out from the brightened scope face. However, limits are imposed by (1) the nature of the phosphor, and (2) the diffusion of the image that occurs as brightness of a small luminous object is increased. At this point, we shall also reconsider what the best background luminance would be for the radarscope. Consider the following data:

In the first place, if the pilot must shift his eyes back and forth from the daylit sky to the radarscope, must the scope be as bright as the sky for the pilot to see it clearly? The answer is, no; a surface up to 100 times less bright than a previously viewed surface can still be seen with little adaptation time. Since the brightness of a daylit sky is about 2000 millilamberts, scope brightness should therefore be set up to 20 mL or higher to ensure visibility of the scope face (without target pips).

Now, how bright must the target signal be to be detected against a background of 20 mL? Figure 8.28 shows that after looking at a sky whose brightness is 2000 mL (i.e., 3.3 log units), the pilot can immediately detect a signal 2.5 times brighter than its background. Figure 8.28 assumes a background luminance of 0.022 mL but Figure 8.12 or curve 4, Figure 8.24, shows that as over-all luminance values increase, lower contrast ratios can be discriminated. Therefore, a signal of 50 mL should be more than bright enough to detect against a background of 20 mL.

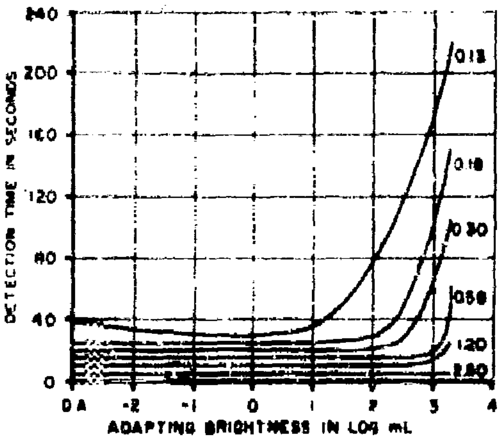


Figure 8.28 Time Required to Detect Signal as a Function of Previous Brightness to Which Subject has Been Adapted, for Several Different Contrasts

To make curves readable, the 0.15-contrast curve has been stepped up 25 seconds, the 0.18 curve, 20 seconds, etc. (after Hanes and Williams[8-22])

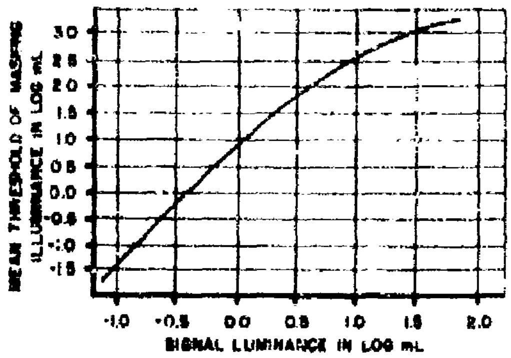


Figure 8.29 The Lowest Ambient Illuminance Required to Prevent a Radar Signal From Being Detected (i.e., Threshold Masking Luminance), Plotted as a Function of Signal Luminance

A trace 15 inches long was used as the signal. (from Adler et al[8-2])

One question remains: how will ambient illumination affect the visibility of scope face and signal? When a radar operator is required to work in illuminated surroundings, ambient light reflected from the face of the cathode ray tube may mask scope signals.

Figure 8.29 shows the results of an experiment which was conducted to find out how much ambient luminance would just prevent a signal from being seen. The signal was a line 15 degrees long, in visual angle subtended. Signals of very low luminance (0.1 mL) are masked by ambient illumination of slightly lower luminance values at the scope face. As signal luminance increases to somewhat higher values, a much greater proportion of ambient luminance is required to mask the signal. At 1 mL (0 log units), for example, the signal can be seen against masking illuminations up to 10 mL. As signal luminances increase further, however, the masking luminance threshold increases at a decreasing rate; it reaches an asymptote at about 1000 mL (3 log units). Thus, when ambient luminance is in the order of 1000 mL, it becomes impractical to make a cathode ray tube signal bright enough to be seen.[8-2]

Figure 8.29 also shows that when a signal of 50 mL (1.7 log units) is used, ambient luminance must be kept below 100 mL; otherwise the signal will not be seen. And since background luminance will be 20 mL, ambient luminance should probably be lowered still further, to less than 80 (i.e., 100 minus 20) mL. A shield against ambient illumination is therefore indicated.

Shape of Signal. In addition to changing color and brightness, the engineer might make the pip easier to detect by designing the input to change its shape. He might also make it bigger, but the position of a large pip cannot be determined accurately.

Figure 8.30 shows minimum contrast that can be discerned as a function of area for rectangles of five different shapes. From this graph, it is apparent that a pip of a given area can be seen at lower contrasts as its shape approaches a square.[8-24]

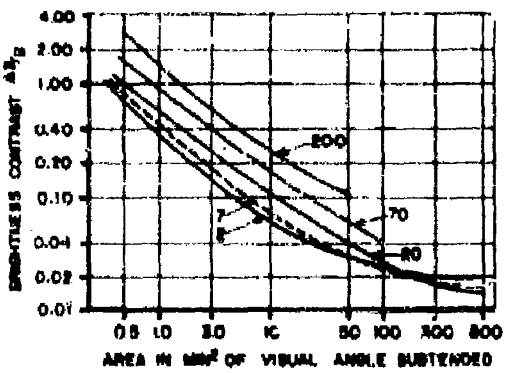


Figure 8.30 Effect of Area of Rectangular Stimulus on Threshold Contrast for Five Ratios of Length to Width of Rectangle (after Lamar et al[8-34])

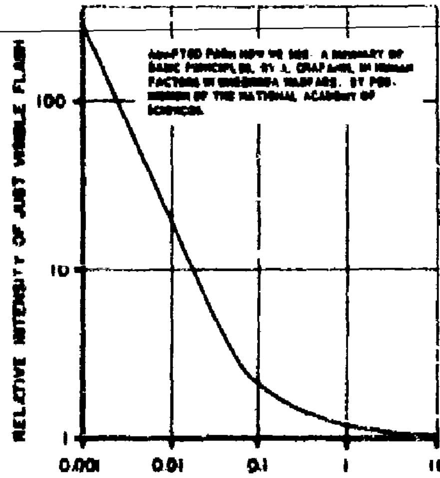


Figure 8.31 Intensity of Just Visible Flashes of Light as a Function of the Duration of the Flash (after Chapanis[8-15]) (data from Blondel and Rey[8-33])

Example D: Duration of Stimulus

Engineering Change. For refueling in the air at night, the position of the fuel ship is given by radio, but a special white light is used to identify the fuel ship within visibility range. If the engineer changes the fuel ship light from a steady white light to a flashing light of the same intensity, will it be more conspicuous? Will the change introduce any undesirable elements in visual performance? The following discussion shows how he would go about finding out.

Effects of Change on Visual Performance

To predict the effects of the flashing light, the engineer again turns to curves 1 through 5 (see Fig. 8.24). He finds:

From curves 1 and 2, that, because the rods are more sensitive than the cones (curve 2), they will pick up the light at a much greater distance than the cones. Therefore, the eye will pick up the light where rods are concentrated, some 20 degrees from the fovea (curve 1), and slightly off-center fixation will follow. A flashing light, however, might be in one of its off periods at the moment during the pilot's scanning that the image would fall on the more sensitive portions of his retina; the flashing light would then not be detected as far away as a steady light.

From curve 3, that if pilot has been observing a radarscope whose brightness is in the order of 50 mL (5×10^{-10} $\mu\mu$ L), he will need time to dark-adapt before he can detect a dim, distant fuel-plane light.

Curve 4 does not apply directly, since it shows contrast thresholds for dark objects of finite size against light backgrounds. However, contrast would be at a maximum with a steady white light at night; in a sense, it is reduced somewhat by the use of a flashing light, since no contrast exists when the light is off.

Curve 5 does not apply; acuity is not crucial in this detection task.

Further Engineering Changes to Improve Visual Performance

Other variables that can be manipulated to improve the situation are the intensity, duration, and size (visual angle subtended) of the stimulus.

Intensity can be increased to make flashing light as visible as steady light.

Duration. The engineer could manipulate the frequency and duration of flashes to increase the visibility of the light. Also, means might be provided for the pilot to dark-adapt before he begins to scan for the light.

The following data will shed some light on the effects of manipulating intensity and duration.

The study whose results are shown in Figure 8.31 was concerned with the intensity required to see a

light whose location was known. Under these circumstances, a flash of light that lasts less than about a half-second must be much more intense than a steady light to be seen. A flash that lasts half a second or longer is almost as visible as a steady light of the same intensity. When the location of the light is not known and the observer must hunt for it, as in our example, a large safety factor must be added to the minimum values given in Figure 8.31.[8-33]

In another study, complex reactions to steady and flashing lights were determined at high contrasts such as exist in our example. It was found that steady light signals were more conspicuous than flashing light signals.[8-35]

In still a third study -- a recent preliminary one -- detection times were compared for various flash rates, on/off ratios, and differences among individual subjects. Flash rates were 40, 60, 80, 100, and 120 flashes per minute. On/off ratios were 1/2, 1/1, 2/1, 3/1, and 4/1. Red and yellow wing-tip lights were simulated as they would appear to a pilot about two miles away from another aircraft. Flash rate was found not to be a factor in detection time, but on/off ratio had a significant effect; ratios below 2/1 were better than those above 2/1.[8-34]

Visual Angle. The engineer can increase the size (and thereby the total energy emitted) of the signal. As in Example B, dealing with runway lights, the engineer can increase the size of the fuel-plane light to make it in effect an extended source rather than a point source. This will increase its visibility, as explained under Example B and illustrated in Figure 8.27.

Example E: Changing Visual Angle Subtended

The example that follows deals with the effects of an engineering change that will change the minimum distinguishable acuity. This and other types of visual acuity have been described earlier in this chapter.

Engineering Change. The size of an individual dial is limited by the number of dials required on an instrument panel and by the permissible panel size. The engineer has the problem of providing more information on a dial that has light letters and numbers against a dark background. Accordingly, he reduces the size of the lettering severely. The pilot is still expected to distinguish the letters and numbers. What will happen?

Effects of Change on Visual Performance

Again turning to curves 1 through 5 (see Fig. 8.24) the engineer finds:

From curves 1 and 2, that, provided the correct colors (i.e., wave lengths) are chosen and the dial is illuminated brightly enough, the cones will be able to respond. Thus, the pilot can use central, foveal vision to read the dial. The graph in Figure 8.25 shows that his visual acuity will be very much better than if he used peripheral, rod vision. However, below a certain letter size for any given luminance, the pilot will still not be able to read the dial (see Fig. 8.27).

From curve 3, that if the pilot is adapted to a fairly low level of illumination, his ability to see a dim dial with cone vision (as well as rod) will be increased.

From curve 4, that numbers and letters may not be distinguishable from their background.

From curve 5, that, at low luminances, they may not be identifiable.

Further Engineering Changes to Improve Visual Performance

If the engineer has set out to reduce letter and digit size, he can improve the situation by altering, for example, the spectral composition or luminance.

Spectral Composition. If he selects a good color -- preferably white -- and transilluminates the letters and digits (that is, puts the light behind them), he can add color contrast to brightness contrast to make the letters stand out. The situation is almost identical to that for Example C, above, dealing with a radarscope; see the study[8-20] cited there.

Luminance. The engineer can increase the luminance of the lettering and produce the best possible contrast. Consider the following study:

Recognition time as a function of digit size and brightness was determined for white dial-type digits on a dark background. The brightness range was from 0.003 to 0.1 ft-L. Average recognition time under the most favorable conditions tried was about 0.6 second. As size or brightness decreased, recognition time increased, at first slowly and then more rapidly. In other words, when size is held constant, less time is required to see at higher luminance levels.[8-18]

Example F: Shape and Spatial Arrangement (Parallel Lines to Identify Aircraft)

There are many ways of varying shape and rearranging objects and displays The following is an ex ple:

Engineering Change. Let us say that it has been suggested that a good way to make planes identifiable is to paint a different number of parallel lines on the fuselage of each type of plane. But the fuselage is not large enough to contain a great number of parallel lines unless the lines are placed very close together. If retroflective material is used, parallel lines very close together appear as dark on a light ground in daylight and luminous on a dark ground at night.

Effects of Change on Visual Performance

Using curves 1 through 5 (see Fig. 8.24) to predict whether a given number of parallel lines can, in fact, be seen clearly enough to identify the aircraft, the engineer finds:

From curve 1, and also from the visual acuity curve in Figure 8.25, that foveal fixation (cones only) will be required both day and night.

From curve 2, that wave length will matter. If violet retroflective material is used, for example, the cone receptors may not be stimulated enough to detect the hues, either by day or night.

From curve 3, that if retroflective material of any color is not luminous enough at night (above about 0.1 millilambert), the cones may not respond adequately, though in daylight their response will be rapid. (In identifying a moving aircraft, one cannot count on having even a brief time to dark-adapt.)

From curve 4, that as luminance increases from night to day conditions, a lower contrast ratio can be discriminated. In this case, contrast ratio must not be too great even at night, since we are dealing with luminous objects.

From curve 5, that even if luminance is high enough for cones to respond, it may not be high enough for the symbol to be identified At daytime levels of illumination, visual acuity may be expected to be better -- within certain limits imposed by the distance at which the plane is to be identified.

Further Engineering Changes to Improve Visual Performance

If the engineer must put parallel bars close together, he will have to manipulate other variables so that they can be discriminated. While he probably cannot expect identification at any great distance, he can improve the situation by manipulating spectral composition and luminance.

Spectral Composition. By choosing material that reflects the wave lengths to which the cones are most sensitive, he will help the cones to pick up the symbol at maximum distance. Indeed, by means of curve 2 (Fig. 8.24) and the hue discrimination curve, Figure 8.16, he might choose two colors that the eye can both respond to easily and discriminate as separate hues -- blue-green (λ = 500 mμ) and yellow-green (λ = 560), for example. Then, he might use fewer lines and "color-code" the plane for better identification.

Luminance and Brightness Contrast. To determine the correct contrast range for day and night, consider the following data:

Figure 8.32 applies to daylight, when the dark bars are seen against a brighter background. If it works out, for example, that each bar and each space between bars subtends a visual angle of 1.4

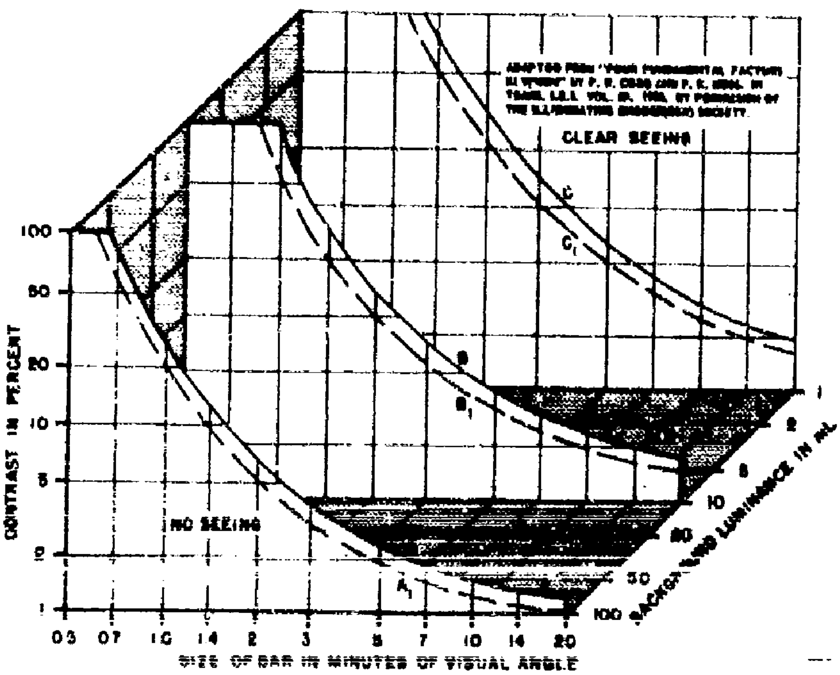


Figure 8.32 Background Luminance and Contrast Required for Bars Subtending Various Visual Angles to be Seen Under Daylight Conditions (after Cobb and Moss 8-17)

minutes at the required recognition distance, contrast must be 50 percent for the individual bars to be discriminated at a background luminance of 1 millilambert. It can be seen that for the intermediate range of visual angles covered in the graph, background luminance is the least important of the three variables. Figure 8.33, however, shows that as the illumination of the bright bars increases beyond about 3.2 photons (0.5 log units), the ability of the eye to discriminate between them begins to get worse instead of better. In other words, reflecting bars by day and luminous bars by night must be bright enough but not too bright; the range of suitable values is narrow. The measure of visual acuity in Figure 8.33 is the smallest distance two bars can be separated and still be seen as separate, expressed in visual angle subtended by that distance.

A factor that will influence the ability of the eye to resolve detail is the relationship between the luminance of the visual task area and the luminance of the "surround" -- the general area surrounding the task area. In our example the visual task area is the fuselage of the aircraft upon which the parallel bars appear, while the "surround" is the sky background. Figure 8.34 shows the effect upon visual acuity when the luminance of the surround varies from less than

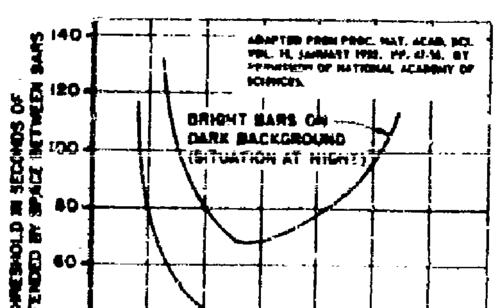


Figure 8.33 Ability to Discriminate Bright Bars Against Dark Background

Plotted as a function of retinal illuminance from bars; ability to discriminate dark bars against bright background, as function of illuminance from background. (after Wilcox 8-33)

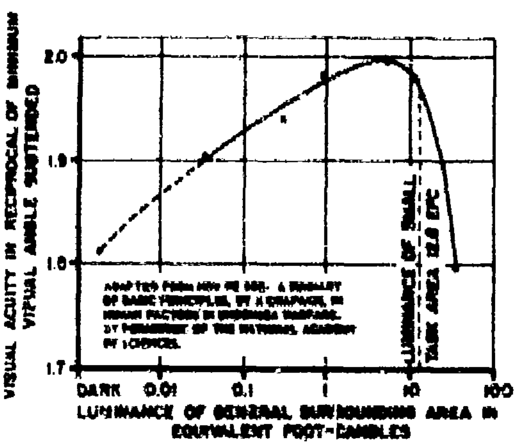


Figure 8.34 How Visual Acuity Varies With the Luminance of the General Surrounding Area When the Immediate Vicinity of the Objects Being Looked at has a Constant Luminance of 12.6 Equivalent Foot-Candles (after Chapanis[8-15]) (data from Lythgoe[8-27])

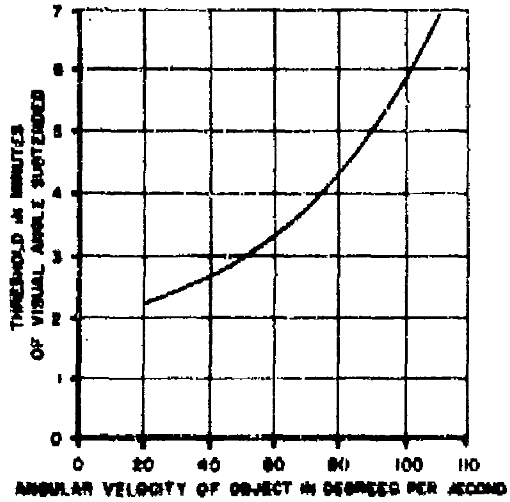


Figure 8.35 Visual Acuity as a Function of Relative Movement Between Observer and Target (data from Ludvigh and Miller[8-29])

that of the task area is greater. It can be seen that acuity is best when the two luminance values are approximately equal; it falls off rapidly as the background luminance is raised above the task luminance. Therefore, if the bars are to be discriminated when the fuselage is viewed in shadow against a bright sky, contrast must be increased; otherwise, recognition distance will be decreased. Data from different experiments conflict on the effects of surround brightnesses lower than that of the task area, but a general rule is to avoid having surrounds less than one tenth as bright as the central field.

Still another factor that will reduce ability to discriminate the parallel bars is relative movement between the observer's aircraft and the aircraft to be identified. The relationship between visual acuity and the angular velocity of a moving target is illustrated in Figure 8.35. In this experiment, the observers were asked to discriminate the orientation of the gap in a Landolt ring moving horizontally. The moving object was visible for 0.4 second at an optical distance of 4 meters under 25 foot-candles of illumination. Figure 8.35 shows that visual acuity is reduced rapidly with increasing angular velocity, and that the rate of reduction increases with increasing angular velocity.

SUMMARY OF TECHNIQUES IN SOLVING VISUAL PROBLEMS

When you have design problems for which no applicable research or operational information exists, we suggest that you:

1. Determine the visual functions required of the operator, as described in the foregoing pages.

2. Determine the tolerance limits that must be maintained for proper performance. What are the criteria for operator performance? Is there a job analysis? What safety factor must be provided?

3. Determine the parameters of the operator's environment that can influence visual performance related to this problem.

4. Determine the design elements subject to engineering modification that may improve the factors in item 3.

5. Determine the "cost" involved in modifying these design elements. Remember that the relation between physical variables and psychophysical performance is frequently nonlinear, so that the modification may require a disproportionate increase in certain factors to obtain a

given degree of improvement in performance. Remember also that part of the "cost" may be effects tending to impair other functions (e.g., raising illumination on one dial may increase adaptation time for another dial).

6. Select factors to be modified and feasible ranges of modification consistent with items 2 and 5.

7. Provide, if possible, a semioperational mockup for study of designs under consideration, so that you will not have the expense of going through the production steps and flight tests with questionable designs. The more environmental factors incorporated, the more precise your conclusions can be. However, completely realistic simulation of external design features is not always worthwhile; the important thing to remember is that the simulator must resemble the real thing in terms of the functions involved.

In the past, research on display characteristics and panel arrangement, for instance, was either of the laboratory type, in which a single instrument was tested in isolation, or was in the form of flight tests, the only data being the opinion of a small number of experienced individuals. However, with the advent of training simulators, the analog computer, etc., it is now relatively easy for the engineer to experiment on his own or with the assistance of a human engineering organization. The influence of one instrument on over-all performance or the efficiency of a whole instrument system can be tested under realistic conditions. The result is objective measures of performance that are relatively economical and can lead to further improvements in the design.

SPECIAL FACTORS INFLUENCING VISUAL PERFORMANCE

Visual Problems Due to Acceleration

The high accelerations achieved by high-performance aircraft can obscure a pilot's vision over a great many miles. When an aircraft turns, pulls out of a dive, rapidly enters a climb, or executes a loop, radial acceleration is produced. The resultant force is applied inward, perpendicular to the tangent of the curve. It is directly proportional to the mass and the square of tangential velocity, and inversely proportional to the radius of the curve. It is measured in g's, one g being equal to the pull of gravity on a stationary object. The physiological effect is due to inertia, and works in the opposite direction. Positive g is applied when the pilot's head is toward the center of curvature, as in a normal turn or dive; the blood is forced toward his feet, and the vision is first dimmed (grayed-out) and then blacked-out. When his feet are toward the center of curvature, as in an outside loop, negative g is applied; blood is forced toward the head, and the more dangerous red-out may occur. When the force is applied from chest to back or vice versa, as in linear acceleration, transverse g is applied; blood is forced toward the pilot's back or front, and the pilot's tolerance to acceleration is much greater. The visual effect of any type of acceleration is a function of time as well as the direction and the amount of force.

Structurally, high-performance aircraft can nearly always withstand forces well over six positive g. But what about the pilot? At 2000 miles an hour, an aircraft could not turn in a circle smaller than 18 miles in diameter. About six g would be applied, and nearly every pilot would be blacked-out during the entire turn -- a total distance of more than 56 miles along the flight path! Even at much lower accelerations, vision is seriously impaired. For instance, in one study it was found that pilots tried to read as many dials at three g as they do at 1.5. At three g, their readings were 24 percent wrong, against 18 percent at 1.5 g -- a statistically significant difference.

"G-suits" can counteract positive g by applying pressure to the lower part of the body, opposite to the g-force. Those devised so far increase tolerance an average of 2.3 g.

Other Causes of Visual Problems in High-Performance Aircraft

Other causes of impaired vision are at work less of the time than speed and acceleration in high-performance aircraft, but their effects can be equally damaging. For example, hypoxia, a lowering of the oxygen supply in the tissues, will never occur under normal conditions, because pilot and crew are required to take supplementary oxygen above 10,000 feet during daylight and from take-off at night. But the supply of oxygen may fail, and if this occurs, vision will be affected earlier and more severely than other sensory processes. The degree of impairment is greater with higher altitudes and, to a lesser degree, with longer duration of exposure.

Another problem is a dark cockpit at high altitudes, where the sun appears as a bright spot of light in a dark sky. There is less diffusion of light from above than at low altitudes, and instruments

not directly in line with the sun's rays are poorly illuminated. Vision becomes worse when light glares from a layer of clouds below the aircraft. Instruments may therefore become impossible to read at high altitudes in broad daylight unless they are lighted artificially.[8-21]

Still another problem is altitude, empty field, or night myopia. When a pilot has no land, lights, or distant objects on which to focus, he may accommodate for something very close without realizing he is doing it. He is temporarily myopic -- near-sighted -- and for practical purposes, "blind" to objects out in space. He may fail to see other aircraft in his central field of vision not far away. The answer to this problem may lie in training pilots to consciously relax their eyes, so that they focus on infinity.

High skin temperatures are not developed by today's standard military aircraft, but they become a grave problem as speeds get into the higher mach numbers. It has been estimated that aircraft going 2000 miles an hour would develop skin temperatures of 600°C (1112°F). Vision is not a critical element in withstanding high ambient temperatures; the eyes can withstand exposure to the hottest air the lungs can breathe, which is 240°F for 15 to 23 minutes. However, refrigeration becomes a necessity at very high speeds, and with it comes the problem of designing thick, insulating windshields that do not distort or obscure.

For structural reasons also, designers tend to make windshields thicker, and, for aerodynamic reasons, more streamlined as speeds get higher. Optical surfaces slanted to different degrees, so that the two eyes are looking at different slants, can produce measurable changes in the ability to distinguish small objects. In addition, both curved and slanted surfaces can produce reflections that can mislead a pilot seriously, and curved surfaces must be carefully designed to keep distortion at a minimum. Similar problems arise in designing visors and goggles.

Other, more special problems arise in high-speed flight. Light rays are bent a little as they pass through the optically denser air in shock waves, causing an apparent displacement of objects from their true position. This displacement varies from speeds of mach 1 to mach [illegible]. Low-frequency vibrations (40 cps) blur vision transiently as the sound barrier is passed.

Effects of Smoking

The most important reaction to smoking is loss of sensitivity to light. There may also be some restriction of the visual field.

The chief offending element in tobacco smoke is not nicotine but carbon monoxide, which enters the lungs when tobacco smoke is inhaled. Blood takes up carbon monoxide from the lungs 210 times more readily than it takes up oxygen. The blood becomes 1 percent saturated with carbon monoxide after only one cigarette (assuming 1 to 2.5 percent of carbon monoxide in the cigarette smoke). It will be more than 5 percent saturated after several hours of heavy smoking. Furthermore, carbon monoxide leaves the blood very slowly; it takes six hours to eliminate half the saturation, and some carbon monoxide is still present in the blood 24 hours after heavy smoking.

Carbon monoxide in the blood means less oxygen; so the effects of smoking parallel those of hypoxia. In a sense, smoking adds to one's "physiological altitude." Figure 8.36 shows the effects of one, two and three cigarettes on visual brightness thresholds. Note that three cigarettes are equivalent to more than seven thousand feet of altitude as far as night vision is concerned, and that it takes over fifteen minutes of breathing pure oxygen to recover the sensitivity thus lost.

Effects of Drinking

Alcohol in the system also produces symptoms like those of hypoxia. The effect of alcohol in the blood is to make body tissues less receptive to the oxygen in the blood. Therefore, the oxygen that is present cannot do its work as effectively.

Drinking reduces depth perception and ability to distinguish between different brightnesses, and it shrinks the visual field to some extent. Heavy drinking reduces light sensitivity. These effects are added to those of hypoxia at any altitude to increase the "physiological altitude."

In addition to its effects on vision, alcohol reduces efficiency of motor performance and ability to think clearly.

Effects of Drugs

Drugs taken to combat disease, tension, and fatigue may have serious effects on vision in flight. It is difficult to generalize about the effects of drugs, because different people react in different ways to the same drug.

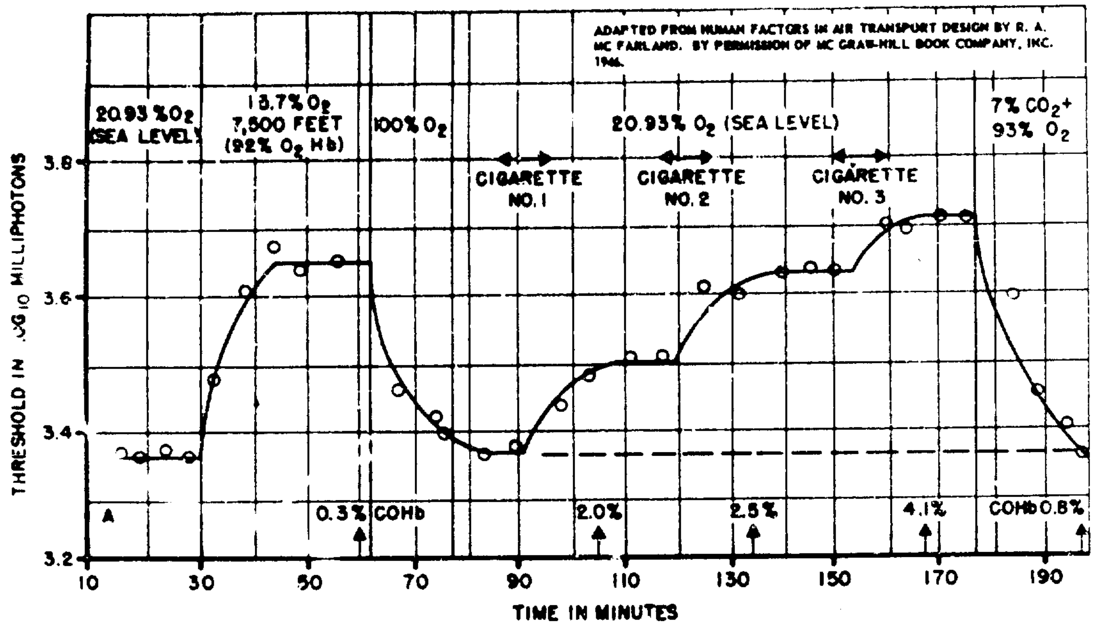


Figure 8.36 The Effect of Smoking on Visual Light Sensitivity as Compared With the Effect of Altitude

The effect of inhaling the smoke of three cigarettes is equal to an altitude of about 8000 feet. (after McFarland [8-29])

Among the drugs that sometimes affect vision are sulfanamides, antihistamines, atabrine, and even aspirin, if used excessively. Their effects may include interference with depth perception and acuity, enlarging of the blind spot, and loss of muscular coordination of the eyes.

Food and Rest

While rest and a sensible diet help to maintain fitness for flight, they are not generally crucial for good visual performance. However, one constituent of diet, sugar, seems to have a direct effect on vision. There is considerable evidence that raising the content of sugar in the blood will reduce some of the effects of hypoxia, particularly loss of light sensitivity. Before flying to high altitudes, a man should therefore eat a meal with some carbohydrate content.

Lack of rest before flight tends to make a flyer tired and sleepy. Among a great variety of symptoms are difficulty in focusing and in keeping the eyes open.

Denitrogenation

When a person ascends fairly rapidly to altitudes above 26,000 feet, the drop in atmospheric pressure causes nitrogen bubbles to form in the blood (among many other effects). If these bubbles are small enough to circulate through the brain, visual disturbances occur. They include hazy vision, restriction of the visual field, and scintillating blind spots.

A pressurized cabin is the best protection against the effects of blood nitrogen bubbles on vision. However, not all cabins are pressurized, and pressure can be lost in those that are. Fortunately, breathing pure oxygen on the ground for 15 minutes before flying reduces the nitrogen content of the blood and tissues and reduces the danger of visual disturbances in flight. This precaution is called "denitrogenation."

Summary of Preflight Procedures

To ensure visual fitness in flight, pilot and crew should (1) dark-adapt as necessary, (2) avoid heavy smoking and drinking, (3) eat a meal of moderately high carbohydrate content before flight, and (4) get rest and relaxation before flight.

Designers should keep in mind that airmen will not always adhere to these rules, especially under the pressures of combat. If possible, equipment and operational tactics should be devised so that a person whose vision is somewhat impaired can still operate the aircraft efficiently.

LIST OF REFERENCES

LIGHT DISCRIMINATIONS

8-1 Anon. Handbook of Human Engineering Data. Tech. Report No. SDC 199-1-1. SDC-ONR. Tufts Inst. for Appl. Exp. Psychol., Medford, Mass. 1949. Revised 1951.

8-2 Adler, H. E., Kuhns, M. P., and Brown, J. L., Masking of CRT Displays by Ambient Illumination. WADC Tech. Report 53-266. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. November 1953.

8-3 Baker, C. A., and Grether, W. F., Visual Presentation of Information. WADC Tech. Report 54-160. August 1954.

8-4 Boring, E. G., Langfeld, H. S. and Weld, H. P., Foundations of Psychology. John Wiley and Sons, New York, N. Y. 1948.

8-5 Chapanis, A., "How We See: A Summary of Basic Principles." Chapter 1 in Human Factors in Undersea Warfare. National Research Council, Washington, D. C. 1949. pp. 3-60.

8-6 Hanson, J. A., A Study of the Pre-exposure Tolerance of the Peripheral Retina. M. S. Thesis, Tufts University, Medford, Mass. June 1956.

8-7 Hecht, S., and Williams, R. E., "The Visibility of Monochromatic Radiation and the Absorption Spectrum of Visual Purple." J. Gen. Physiol. Vol. 5. 1922. pp. 1-33.

8-8 Hill, N. E. G., "The Recognition of Coloured Light Signals which are Near the Limit of Visibility." Proc. Physical Soc. London, Eng. Vol. 89. 1947. pp. 560-574.

8-9 Johannsen, D. E., McBride, P. I., and Wulfeck, J. W., "Studies on Dark Adaptation. I. The Pre-exposure Tolerance of the Dark-Adapted Fovea." J. Opt. Soc. Amer. Vol. 46. No. 1. 1956. pp. 67-71.

8-10 Johannsen, D. E., McBride, P. I., and Wulfeck, J. W., "Studies on Dark Adaptation. II. The Pre-exposure Tolerance of the Human Fovea Adapted to Different Brightness Levels." J. Opt. Soc. Amer. Vol. 46. No. 4. 1956. pp. 266-269.

8-11 Jones, T., Illum. Engng. Soc., ix. 1914. p. 687.

8-12 Osterberg, G., "Topography of the Layer of Rods and Cones in the Human Retina." Acta Ophthalmol. Suppl. Vol. 61. 1935. pp. 1-102.

8-13 Sloan, L. S., "Rate of Dark Adaptation and Regional Threshold Gradient of the Dark-Adapted Eye: Physiologic and Clinical Studies." Amer. J. Ophthal. Vol. 30. 1947. pp. 705-719.

8-14 Steindler. Sitz. Wien. Ak. 1906.

8-15 Stevens, S. S., "Mathematics, Measurement, and Psychophysics." Handbook of Experimental Psychology. S. S. Stevens (Editor). John Wiley and Sons, New York, N. Y. 1951.

SPATIAL DISCRIMINATION

8-16 Chapanis, A., "How We See: A Summary of Basic Principles." Chapter 1 in Human Factors in Undersea Warfare. National Research Council, Washington, D. C. 1949. pp. 3-60.

8-17 Cobb, P. W. and Moss, F. K., "Four Fundamental Factors in Vision." Trans. Illum. Engng. Soc. Vol. 23. 1928. pp. 496-506.

SPATIAL DISCRIMINATION (Cont)

8-18 Crook, M. N., and Baxter, F., Recognition Time for Dial-type Numerals as a Function of Size and Brightness. WADC Tech. Report 6464. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. March 1951.

8-19 Duke-Elder, W. S., Text-Book of Ophthalmology. Vol. 1. Henry Kimpton, London, England. July 1946.

8-20 Eastman Kodak Company. Influence of Color Contrast on Visual Acuity. Nat'l Def. Res. Comm. OSRD Report No. 4541. 1944.

8-21 Haber, H., The Physical Environment of the Flyer. USAF. School of Aviation Medicine, Randolph Field, Texas. vi. 1954.

8-22 Hanes, R. M., and Williams, S. B., "Visibility on Cathode-ray Tube Screen: The Effects of Light Adaptation." J. Opt. Soc. Amer. Vol. 38. 1948. pp. 363-377.

8-23 Hillman, B., Connolly, K., and Farnsworth, D., Color Perception of Small Stimuli with Central Vision. BuMed & Surg., New London, Conn. Report 257. October 1954.

8-24 Lamar, E. S., Hecht, S., Shlaer, S., and Hendley, C. D., "Size, Shape, and Contrast in Detection of Targets by Daylight Vision." I. Data and Analytical Description. J. Opt. Soc. Amer. Vol. 37. 1947. pp. 531-543.

8-25 Lash, J. D., and Prideaux, G. F., "Visibility of Signal Lights." Illum. Engng. Vol. 38. 1943. pp. 481-492.

8-26 Ludvigh, E., and Miller, J. W., A Study of Dynamic Visual Acuity. Joint Project Report No. NM001075, 01.01, Pensacola, Fla.: Kresge Eye Institute and Naval School of Aviation Medicine. 1953.

8-27 Lythgoe, R. J., The Measurement of Visual Acuity. Spec. Rep. Ser., MRC, London, England. 1932.

8-28 Mandelbaum, J., and Rowland, L. S. Central and Paracentral Visual Acuity at Different Levels of Illumination. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. Project No. 220. Report No. 1. June 1944.

8-29 McFarland, R. A., Human Factors in Air Transportation: Occupational Health and Safety. McGraw-Hill Book Co., Inc., New York, N. Y. 1953.

8-30 Wertheim, T., "Uber die underekts Sehscharfe." Z. Psychol. Vol. 7. 1894. pp. 172-187.

8-31 Whitmer, C. Z., "Peripheral Form Discrimination under Dark Adaptation." J. Gen. Psychol. Vol. 9. 1933. pp. 405-419.

8-32 Wilcox, W. W.,"The Basis of the Dependence of Visual Acuity on Illumination." Proc. Nat. Acad. Sci. Vol. 13. 1932. pp. 47-56.

TEMPORAL DISCRIMINATION

8-33 Blondel, A., and Rey, J., "Sur la Perception des Lumière Brêves a la Limite de Leur Portee." J. Phys. Paris. 1911. 1. pp. 530-550.

8-34 Crumley, L. M., and Atkinson, W., Human Engineering Investigation of the Exterior Lighting of Naval Aircraft. Part I. A Study of the Effect of Flash Rate and On-off Ratio on the Detectability of Flashing Lights. Nav. Air Mat. Center, Philadelphia, Pa. Aero Med. Equip. Lab. Report TED NAM EL 52003. September 23, 1954.

TEMPORAL DISCRIMINATION (Cont)

8-35 Gerathewohl, S. J., Conspicuity of Flashing and Steady Light Signals: II. High Contrasts. Project 21-24-014. Report No. 2. 1952.

GENERAL BIBLIOGRAPHY

8-36 Anon. Flight Surgeon's Manual. USAF Manual 160-5. 1954.

8-37 Anon. High Speed Flight Information for Pilots. SDC-ONR. 1951.

8-38 Anon. Bibliography on the Effects of Acceleration, Vibration and Noise on the Human Body. Bostrom Manufacturing Company, Milwaukee, Wis. June 1956.

8-39 Anon. Effect of Bright Sunlight on Subsequent Dark Adaptation. Admiralty Research Lab., Tuddington, Middlesex, England. ARL/N.1/84.11/0. August 1943.

8-40 Anon. U. S. Navy. BuMed & Surg. BuMed News 2, No. 10. May 1944.

8-41 Anon. Army-Navy-OSRD Vision Committee. Minutes and Proceedings of the Sixth Meeting. October 12, 1944. pp. 21-22. (CONFIDENTIAL)

8-42 Anon. Great Britain Air Ministry. Quarterly Bull. of the Director-General of Medical Services, Royal Air Force. December 1953. p. 4.

8-43 Anon. The Science of Color. Committee on Colorimetry. Optical Society of America. Thomas Y. Crowell Company, New York, N. Y. 1953.

8-44 Adams, J. K., Fowler, H. M., and Imus, H. A., The Relationship of Visual Acuity to Acuity of Stereoscopic Vision. Contract OEMsr-815, OSRD Report 2087. OSRD, Brown University. September 1943.

8-45 Adams, O. S., Fitts, P. M., Rappaport, M., and Weinstein, M., "Relations among Some Measures of Pattern Discriminability." J. Exp. Psychol. Vol. 48. 1954. pp. 81-88.

8-46 Alluisi, E. A., Measured Visual Acuity as a Function of Phenomenal Size. Project 7186. WADC Tech. Report 55-384. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. October 1955.

8-47 Alluisi, E. A., Inaba, K., and Nungesser, F. L., Jr., Changes in Visual Depth Perception with the Wearing of Contact Lenses. U. S. Army Medical Research Lab, Report No. 105 III. 1952.

8-48 Alphern, M., and Hendley, C. D., "Visual Functions as Indices of Physiological Changes in the Acid-Base Balance of the Blood." Amer. J. Optom. and Amer. Acad. Optom., Monograph 139. June 1952.

8-49 Alphern, M., and Spencer, R. W., "Variation of Critical Flicker Frequency in the Nasal Visual Field." A.M.A. Arch. Ophthal. Vol. 50. July 1953. pp. 50-63.

8-50 Anderson, J. R., "Some Aspects of Visual Fusion in Peace and War." Trans. Ophthal. Soc. Australia. Vol. 2. 1940. pp. 19-26.

8-51 Andrews, T. G., Methods of Psychology. John Wiley and Sons, New York, N. Y. 1948.

8-52 Ansbacher, H. L., "Distortion in the Perception of Real Movement." J. Exp. Psychol. Vol. 34. February 1944. pp. 1-23.

8-53 Arnoult, M. D., Accuracy of Shape Discrimination as a Function of the Range of Exposure Intervals. Project No. 509-019-0001, Research Bull. 51-32. HRRC, Air Training Command, Lackland Air Force Base, San Antonio, Texas. December 1951.

8-54 Asher, H., "The Suppression Theory of Binocular Vision." Amer. J. Ophthal. Vol. 31. 1954. pp. 246-251.

8-55 Baker, H. D., "Some Direct Comparisons between Light and Dark Adaptation." J. Opt. Soc. Amer. Vol. 45. 1955. pp. 839-844.

8-56 Baker, H. D., "The Instantaneous Threshold and Early Dark Adaptation." J. Opt. Soc. Amer. Vol. 43. 1953. pp. 798-803.

8-57 Baker, H. D., The Course of Foveal Light Adaptation Measured by the Threshold Intensity Increment. 1949.

8-58 Baker, K. E., Some Variables Influencing Vernier Acuity 1. Illumination and Exposure Time. 2. Wave-Length of Illumination. 1949.

8-59 Barmack, J. E., and Coakley, J. D., A Method of Increasing the Maneuverability of High Speed Aircraft within the Limits of Human Tolerance to g Forces. Special Devices Center, Report No. 151-1-11, Project No. 20-M-1b, Contract N6-ori-151, Project Designation No. NR-783-004. February 1948.

8-60 Bartley, S. H.,"The Psychophysiology of Vision." Handbook of Experimental Psychol. S. S. Stevens (Editor). John Wiley and Sons, New York, N. Y. 1951.

8-61 Bartley, S. H., "Some Factors in Brightness Discrimination." Psychol. Rev. Vol. 46. 1939. pp. 337-358.

8-62 Bartley, S. H., and Wilkinson, F. R., "Some Factors in the Production of Gamma Movement." J. Psychol. Vol. 36. 1953. pp. 201-206.

8-63 Battersby, W. S., and Jaffe, R., "Temporal Factors Influencing the Perception of Visual Flicker." J. Exp. Psychol. Vol. 46. 1953. pp. 154-161.

8-64 Beard, M. G., "Cockpit Instrument Panels Standardized." SAE Journal. 60(6). 1952. pp. 50-51.

8-65 Beebe-Center, J. G., Mead, L. C., Wagoner, K. S., and Hoffman, A. C., "Visual Acuity and Distance of Observation." J. Exp. Psychol. Vol. 35. December 1945. pp. 473-484.

8-66 Benson, O. O., Effect of Centrifugal Force on Posture, Vision, and Consciousness. U. S. Army Air Forces, Materiel Division, Experimental Engineering Sect., Ser. No. EXP-M-54-653-41B. September 5, 1941.

8-67 Berger, C., "A Comparison, under Different Degrees of Brightness, of Minimum Visual Distances of Two Luminous Points and of a Broken Circle." Amer. J. Psychol. Vol. 55. 1942. pp. 354-370.

8-68 Berger, C., McFarland, R. A., Halperin, M. H., and Niven, J. I., "The Effect of Anoxia on Visual Resolving Power." Amer. J. Psychol. Vol. 56. July 1943. pp. 395-407.

8-69 Berry, R. N., "Quantitative Relations among Vernier, Real Depth, and Stereoscopic Depth Acuities." J. Exp. Psychol. Vol. 38. December 1948. pp. 708-721.

8-70 Berry, R. N., Riggs, L. A., and Duncan, C. P., "The Relation of Vernier and Depth Discrimination to Field Brightness." J. Exp. Psychol. Vol. 40. No. 3. June 1950. pp. 349-354.

8-71 Berry, R. N., Riggs, L. A., and Richards, W., "The Relation of Vernier and Depth Discrimination to Width of Test Rod." J. Exp. Psychol. Vol. 40. August 1950. pp. 520-522.

8-72 Bevan, W., and Dukes, W. F., "Color as a Variable in the Judgment of Size." Amer. J. Psychol. Vol. 66. April 1953. pp. 283-288.

8-73 Bevan, W., and Dukes, W. F., "Value and the Weber Constant in the Perception of Distance." Amer. J. Psychol. Vol. 64. October 1951. pp. 580-584.

8-74 Birren, J. E., Fisher, M. B., Vollmer, E. P., and King, B. G. Project X-293, Report 2. February 20, 1946.

8-75 Birren, J. E., Stormont, R. T., and Fisher, M. B. U. S. Naval Medical Research Institute. Research Project X-278, Report 1. June 26, 1944. (CONFIDENTIAL)

8-76 Bitterman, M. E., and Krauskopf, J., Some Determinants of the Threshold for Visual Form. WADC Tech. Report 53-331. Aero Medical Lab. Contract No. AF 33(616)-63, RDO No. 694-41. September 1953.

8-77 Bitterman, M. E., Ryan, T. A., and Cottrell, C. L., "Muscular Tension as an Index of Visual Efficiency: A Progress Report." Illum. Engng. [illegible]

8-78 Blum, H., "The Physiological Effects of Sunlight on Man." Physiol. Rev. Vol. 25. 1945. pp. 483-530.

8-79 Blum, H. F., Army-Navy-OSRD Vision Committee, Minutes and Proceedings of the Sixth Meeting. October [illegible], [illegible]. pp. [illegible]. (CONFIDENTIAL)

8-80 Bouman, M. A., On The Relation between Contrast Thresholds and the Light Perception in the Early Stages of Dark Adaptation. National Defense Research Council of the Netherlands, Werkgroep Waarneming, Rijksverdedigingsorganisatie T.N.O., Report No. WW 1952-19.

8-81 Bouman, M. A.,"Peripheral Contrast Thresholds for Various and Different Wavelengths for Adapting Field and Test Stimulus." J. Opt. Soc. Amer. Vol. 42. November 1952. pp. 820-831.

8-82 Bouman, M. A., "Peripheral Contrast Thresholds of the Human Eye." J. Opt. Soc. Amer. Vol. 40. December 1950. pp. 825-832.

8-83 Bouman, M. A., and Van Den Brink, G., "Absolute Thresholds for Moving Point Sources." J. Opt. Soc. Amer. Vol. 43. October 1953. pp. 895-898.

8-84 Boynton, R. M., and Triedman, M. H., "A Psychophysical and Electrophysiological Study of Light Adaptation." J. Exp. Psychol. Vol. 46. No. 2. August 1953. pp. 125-134.

8-85 Bridges, Cecil C., and Bitterman, M. E., "The Measurement of Auto-Kinetic Movement." Amer. J. Psychol. Vol. 67. 1954. pp. 525-529.

8-86 Bridgman, C. S., "Luminosity Curve as Affected by the Relation between Rod and Cone Adaptation." J. Opt. Soc. Amer. Vol. 43. 1953. pp. 733-737.

8-87 Bridgman, C. S., "The Correction of Low Intensity Luminance Functions for the Purkinje Effect." J. Opt. Soc. Amer. Vol. 42. No. 11. November 1952. pp. 832-835.

8-88 Brooke, R. T., "The Variation of Critical Fusion Frequency with Brightness at Various Retinal Locations." J. Opt. Soc. Amer. Vol. 41. No. 12. December 1951. pp. 1010-1016.

8-89 Brown, J. L., Graham, C. H., Leibowitz, H., and Ranken, H. B., "Luminance Thresholds for the Resolution of Visual Detail during Dark Adaptation." J. Opt. Soc. Amer. Vol. 43. No. 3. March 1953. pp. 197-202.

8-90 Brown, J. L., and Lechner, M., Acceleration and Human Performance: A Survey of Research. Project No. NM 001-111, Study No. NM 001-111, Task 300, NADC-MA-5503, Report No. 1. U. S. Naval Air Development Center, Aviation Medical Acceleration Lab., BuMed & Surg., Johnsville, Pa. March 1955.

8-91 Brown, J. F., and Voth, A. C., "The Path of Seen Movement as a Function of Vector-Field." Amer. J. Psychol. Vol. 49. October 1937. pp. 543-563.

8-92 Brown, K. T., Studies on Rate of Apparent Change as a Function of Observation Time, Using a New Type of Dynamic Ambiguous Figure. WADC Tech. Report 54-139. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. May 1954.

8-93 Brown, K. T., "Factors Affecting Rate of Apparent Change in a Dynamic Ambiguous Figure as a Function of Observation Time." WADC Tech. Report 53-482. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. December 1953.

8-94 Brown, K. T., "Methodology for Studying Figure After-Effects and Practice Effects in the Müller-Lyer Illusion." Amer. J. Psychol. Vol. 66. No. 4. October 1953. pp. 629-634.

8-95 Brown, R. H., "Velocity Discrimination and the Intensity-Time Relation." J. Opt. Soc. Amer. Vol. 45. 1955. pp. 189-192.

8-96 Brown, R. H., and Conklin, J. E., "The Lower Threshold of Visible Movement as a Function of Exposure Time." Amer. J. Psychol. Vol. 67. 1954. pp. 104-110.

8-97 Browne, R. C., and Illingworth, R. S., Experiments Regarding Ocular Functions in Relation to Anoxia. Great Britain. Flying Personnel Research Committee Report No. 155a. May 1940.

8-98 Browne, R. C., Illingworth, R. S., and Mole, R. H., Effect of Anoxaemia on Ocular Function. Great Britain. Flying Personnel Research Committee Report No. 155b. May 1940.

8-99 Burian, H. M., "Influence of Prolonged Wearing of Meridional Size Lenses on Spatial Localization." Arch. Ophthal. Vol. 30. 1943. pp. 645-666.

8-100 Campbell, P. A., Possible Effects of Small Daily Doses of Sulfadiazine on Flying Personnel. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. Project No. 293, Report No. 1. July 29, 1944.

8-101 Canfield, A. A., Comrey, A. L., Wilson, R. C., and Zimmerman, W. S., "The Effect of Increased Positive Radial Acceleration upon Discrimination Reaction Time." J. Exp. Psychol. Vol. 40. December 1950 pp. 733-737.

8-102 Chalmers, E. L., "The Role of Brightness in Primary Size-Distance Perception." Amer. J. Psychol. Vol. 66. 1953. pp. 584-592.

8-103 Chalmers, E. L., "Monocular and Binocular Cues in the Perception of Size and Distance." Amer. J. Psychol. Vol. 65. 1952. pp. 415-423.

8-104 Chun, Grace S., Barmack, J. E., and Coakley, J. D., The Effects of Ultrasonic Vibrations on Man. Special Devices Center, Report No. 151-1-15, Project No. 20-M-1b, Contract N6-ori-151, Project Designation No. NR-783-004. April 15, 1948.

8-105 Chantraine, H., Jedermann Kann Raumlich Sehn Lernen, Rontgenpraxis 12:415. (German) 1940. pp. 455-461.

8-106 Chapanis, A., Evaluation of the "Contrast Discrimination Test" as an Anoxia Demonstration Device. U. S. Army Air Forces, Air Technical Service Command, Engineering Division, Aero Medical Lab., Ser. No. TSEAA-695-65. March 1, 1946.

8-107 Chapanis, A., and McCleary, R. A., "Interposition as a Cue for the Perception of Relative Distance." J. Gen. Psychol. Vol. 48. 1953. pp. 113-132.

8-108 Cheatham, P. G., A Comparison of the Visual and Auditory Senses as Possible Channels for Communication. U. S. Air Force Tech. Report No. 5919, Air Materiel Command, Wright-Patterson Air Force Base, Ohio. May 1950.

8-109 Cibis, P. A., Retinal Adaptation in Night Flying. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. Project 21-31-014. 1952.

8-110 Cibis, P. A., Gerathewohl, S. J., and Rubenstein, D., Depth Perception in Monocular and Binocular Vision. USAF School of Aviation Medicine. Report. 1953.

8-111 Clark, B., and Graybiel, A., "Visual Perception of the Horizontal Following Exposure to Radial Acceleration on a Centrifuge." J. Compar. Physiol. Psychol. Vol. 44. 1951. pp. 525-534.

8-112 Clark, B., and Graybiel, A., "Apparent Rotation of a Fixed Target Associated with Linear Acceleration in Flight." Amer. J. Ophthal. Vol. 32. 1949. pp. 549-557.

8-113 Clark, B., Johnson, M. L., and Dreher, R. E., "The Effect of Sunlight on Dark Adaptation." Amer. J. Ophthal. Vol. 29. 1946. pp. 828-836.

8-114 Clark, W. B., and Johnson, M. L., The Course of Dark Adaptation after Wearing Orange Dark Adaptor Goggles. U. S. Naval Air Station, Pensacola, Fla. School of Aviation Medicine and Research, Project X-439 (Av-230-p), Report No. 1. February 19, 1945.

8-115 Cole, E. L., Milton, J. L., and McIntosh, B. B., Routine Maneuvers under Day and Night Conditions Using an Experimental Panel Arrangement. WADC Tech. Report 53-220. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. March 1954.

8-116 Comprey, A. L., Canfield, A. A., Wilson, R. C., and Zimmerman, W. S., "The Effect of Increased Positive Radial Acceleration upon Perceptual Speed Ability." J. Aviat. Med. Vol. 22. 1951. pp. 60-64.

8-117 Conklin, J. E., Baldwin, A., and Brown, R. H., "Apparatus for Measuring the Threshold for Visual Discrimination of Direction of Movement." Amer. J. Psychol. Vol. 66. 1953. pp. 289-294.

8-118 Connell, S. C., and Grether, W. F., Psychological Factors in Check Reading of Single Instruments. USAF Air Materiel Command, Memo Report No. MCREXD-694-17A. September 1948.

8-119 Craik, K. J. W., Visual Data. Cambridge University, Psychological Lab. July 13, 1944.

8-120 Craik, K. J. W., The Effect of Glucose on Night Vision in Anoxic Subjects. Great Britain. Flying Personnel Research Committee Report No. 304b, OSRD Liaison Office Ref. No. WA-10-4C. June 20, 1941.

8-121 Creed, R. S., and Ruch, T. C., "Regional Variations in Sensitivity to Flicker." J. Physiol. Vol. 74. 1932. pp. 407-423.

8-122 Cronbach, L. J., Some Current Studies of Visual Perception. Tech. Report ONRL-1-56. Office of Naval Research, London, England. January 1956.

8-123 Crook, D. J., Hanson, J. A., McBride, P. L., and Wulfeck, J. W., A Bibliography on Dark Adaptation. Armed Forces-National Research Council Vision Committee Secretariat, University of Michigan, Ann Arbor, Mich. (Tufts College) July 1953.

8-124 Crook, M. N., "Visual Discrimination of Movement." J. Psychol. Vol. 3. 1937. pp. 541-558.

8-125 Crook, M. N., Harker, G. S., Hoffman, A. C., Wulfeck, J. W., and Kennedy, J. L., Amplitude Thresholds for Visual Perception of Vibration. Contract W33-038-ac-14559, Memo Report MCREXD-694-1R, Report 6. Aero Medical Lab., Engineering Div., Air Materiel Command, Wright Field. (Tufts College, Medford, Mass.) December 1948.

8-126 Crouch, C. L., and Freyer, E., Visual Effectiveness of Flashing Light Sources. February 1952.

8-127 Crozier, W. J., "On the Sensory Discrimination of Intensities." Proc. Nat. Acad. Sci. Wash. D.C. Vol. 22. 1936. pp. 412-416.

8-128 Crozier, W. J., "On the Variability of Critical Illumination for Flicker Fusion and Intensity Discrimination." J. Gen. Physiol. Vol. 19. 1936. pp. 503-522.

8-129 Crozier, W. J., and Wolf, E., "Theory and Measurement of Visual Mechanisms V. Flash Duration and Critical Intensity for Response to Flicker." J. Gen. Physiol. Vol. 24. 1941. pp. 635-654.

8-130 Crozier, W. J., and Wolf, E., "Theory and Measurement of Visual Mechanisms VI. Wave-Length and Flash Duration in Flicker." J. Gen. Physiol. Vol. 25. 1941. pp. 89-110.

8-131 Dartnall, H. J. A., "The Interpretation of Spectral Sensitivity Curves." Brit. Med. Bull. Vol. 9. 1953. pp. 24-31.

8-132 Davidson, W. Z., The Effects of Two Types of Stress and Anxiety on Performance of a Perceptual Task. Contract DA 49-007-md-222, Tech. Report 19, Maryland University, College Park, Md. August 1953.

8-133 Davy, E., "The Intensity-Time Relation for Multiple Flashes of Light in the Peripheral Retina." J. Opt. Soc. Amer. Vol. 42. December 1952. pp. 937-941.

8-134 Detherage, Bruce H., "Figural After-Effects in Stroboscopic Movement." Amer. J. Psychol. Vol. 67. 1954. pp. 259-267.

8-135 DeGroot, S. G., Dodge, J. M., and Smith J. A., Factors in Night Vision Sensitivity: III. The Interrelationships of Size, Brightness, and Location. NRL Report No. 234. September 14, 1953.

8-136 De Vries, Hl., "The Luminosity Curve of the Eye as Determined by Measurements with the Flickerphotometer." Physica. Vol. 14. June 1948. pp. 319-348.

8-137 De Vries, Hl., "On the Basic Sensation Curves of the Three-Color Theory." J. Opt. Soc. Amer. Vol. 36. March 1946. pp. 121-127.

8-138 Diamond, A. L., "Foveal Simultaneous Brightness Contrast as a Function of Inducing and Test-Field Luminances." J. Exp. Psychol. Vol. 45. May 1953. pp. 304-314.

8-139 Diamond, A. L., and Gilinsky, A. S., Luminance Thresholds for the Resolution of Visual Detail during Dark Adaptation Following Different Durations of Light Adaptation. RDO 694-48, Tech. Report 52-237, WADC, Wright-Patterson Air Force Base, Ohio. April 1952.

8-140 Dichman, B., Preston, B., and Mull, H. K., "Distance Judgment in Bright and Dim Light." Amer. J. Psychol. Vol. 57. 1944. pp. 83-84.

8-141 Dill, D. B., Night-Blindness. U. S. Army Air Forces, Materiel Division, Experimental Engineering Section. November 10, 1941.

8-142 ten Doesschate, G., and Fischer, F. P., "Ueber Darstellen und Betrachten der Perspektive." Ophthalmologica. Vol. 97. 1939. pp.1-19.

8-143 Edwards, A. S., "The Relation of Light Intensity to Accuracy of Depth Perception." J. Appl. Psychol. Vol. 37. 1953. pp. 300-301.

8-144 Edwards, W., "Autokinetic Movement of Very Large Stimuli." J. Exp. Psychol. Vol. 48. 1954. pp. 493-495.

8-145 Edwards, W., "Two- and Three-Dimensional Autokinetic Movement as a Function of Size and Brightness of Stimuli." J. Exp. Psychol. Vol. 48.No. 5. November 1954. pp. 391-398.

8-146 Ekman, G., "Dimensions of Color Vision." J. Psychol. Vol. 38. 1954. pp. 467-474.

8-147 Ekman, G., Discrimination of Hue as a Function of Wave Length. Report from the Psychol. Lab., University of Stockholm. No. 19. May 1955.

8-148 Ekman, G., A Note on the Normal Probability Function in Color Vision. Report from the Psychol. Lab., University of Stockholm. No. 17. April 1955.

8-149 Eriksen, C. W., Multidimensional Stimulus Differences and Accuracy of Discrimination. WADC Tech. Report 54-165. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. June 1954.

8-150 Eriksen, C. W., Partitioning and Saturation of the Perceptual Field and Efficiency of Visual Search. WADC Tech. Report 54-161. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. 1954.

8-151 Eriksen, C. W., "Object Location in a Complex Perceptual Field." J. Exp. Psychol. Vol. 45. No. 2. 1953. pp. 126-132.

8-152 Flang, H. S., Hall, A. L., and Hwang, T. F., The Influence of Prolonged Stay in the Dark on Foveal Dark Adaptability. Project NM 001 059.30.01. U. S. Naval School of Aviation Medicine, N.A.S., Pensacola, Fla. October 1953.

8-153 Faucett, R. E., The Effect of Dramamine on Visual and Auditory Acuity. Project NM 002 015.09.01, Report No. 222. Medical Research Lab., U. S. Naval Submarine Base, BuMed & Surg., Navy Dept., New London, Conn. April 1953.

8-154 Ferree, C. E., and Rand, G., "A Convenient and Practical Means for Studying Light and Color Minima in Any Part of the Retina." J. Exp. Psychol. Vol. 26. 1940. pp. 22-52.

8-155 Ferree, C. E., and Rand, G., "Visibility of Objects as Affected by Color and Composition of Light. Part II. With Lights Equalized in Both Brightness and Saturation." Person. J. Vol. 10. 1931. pp. 108-124.

8-156 Ferree, C. E., and Rand, G., "Visibility of Objects as Affected by Color and Composition of Light. Part I. With Lights of Equal Luminosity or Brightness." Person. J. Vol. 9. 1931. pp. 475-592.

GENERAL BIBLIOGRAPHY (Cont)

8-157 Fitts, P. M., and Simon, C. W., The Arrangement of Instruments, the Distance between Instruments, and the Position of Instrument Pointers as Determinants of Performance in an Eye-Hand Coordination Task. USAF Tech. Report No. 5832. February 1952.

8-158 Floyd, W. F., and Welford, A. T., Symposium on Fatigue. 1953.

8-159 Franklin, D. A., "Phi Phenomenon and Parallax (Motion and Binocular)." Amer. J. Ophthal. Vol. 34. January 1951. pp. 77-83.

8-160 Fraser, D. C., A Study of Fatigue in Aircrew. Interim Report I. Validation of Technique. Great Britain. Medical Research Council, Applied Psychol. Research Unit, Cambridge. APU 185/52. December 1952.

8-161 Frey, R. G., "Relation between Visual Acuity and Depth Perception." Wien Med. Wschr. Vol. 103. 1953. pp. 436-438.

8-162 Fry, G. A., "A Re-Evaluation of the Scattering Theory of Glare." Illum. Engng. Vol. 49. No. 2. February 1954. pp. 98-102.

8-163 Fry, G. A., "Further Comments on Luneburg's Analysis of Binocular Vision." Amer. J. Ophthal. Vol. 29. 1952. pp. 260-262.

8-164 Gassovskii, L. N., and Nikolskaia, N. A., "Magnitude of the Threshold of Stereoscopic Vision as Affected by the Period of Observation." C. R. Acad. Sci. U.S.S.R. Vol. 38(1). 1943. pp. 15-17.

8-165 Gebhard, J. W., Preliminary Recommendations on the Types of Visual Codes Proposed for the Integrated Electronic Display. Office of Naval Research, Special Devices Center Report 166-1-105. November 1, 1949.

8-166 Geldard, F. A., The Human Senses. John Wiley and Sons, New York, N. Y. 1953.

8-167 Gerathewohl, S. J., "Conspicuity of Flashing Light Signals of Different Frequency and Duration." J. Exp. Psychol. Vol. 48 1954. pp. 247-251.

8-168 Germain, A. V., St., "Physiological Aspects of Interplanetary Travel." Amer. Helicopter. Vol. 21 (2). January 1951. pp. 10-12 and 19.

8-169 Gibson, E. J., and Bergman, R., "The Effect of Training on Absolute Estimation of Distance." J. Exp. Psychol. Vol. 48. 1954. pp. 473-482.

8-170 Gibson, E. J., and Smith, J., The Effect of Training in Distance Estimation on the Judgment of Size-at-a-Distance. Project 509-019-0002, Research Bull. 52-39. HRRC, Air Training Command, Lackland Air Force Base, San Antonio, Texas. (Cornell University) December 1952.

8-171 Gibson, J. J., "The Visual Perception of Objective Motion and Subjective Movement." Psychol. Rev. Vol. 61 1954. pp. 304-314.

8-172 Gibson, J. J., and Robinson, J. S., The Effectiveness of an Abrupt Change in Texture-Density as a Stimulus for the Impression of Depth-at-an-Edge. U S Air Force, Air Research and Development Command, Human Resources Research Center, Lackland Air Force Base, San Antonio, Texas Research Note P & MS: 52-2, Project 509-019-0002, HRRC 1-154-52, Cornell University. February 1952.

8-173 Gilbert, M., "Definition of Visual Acuity." Brit. J. Ophthal. Vol. 37 1953. pp. 661-669.

8-174 Gilinsky, Alberta S., Perception of Size of Objects at Various Distances. USAF Personnel Training Research Center. Research Bull. No. AFPTRC-TR-54-92 iv

8-175 Gogel, W. C., The Perception of the Relative Depth Position of Objects as a Function of the Other Objects in the Field of View. U. S. Army Medical Research Lab. Report No. 107 ii. 1953.

8-176 Gogel, W. C., and Harker, G. S., "The Effectiveness of Size Cues to Relative Distance as a Function of Lateral Visual Separation." J. Exp. Psychol. Vol. 50. November 1955. pp. 309-315.

8-177 Gogel, W. C., Tammaro, J. P., and Inaba, K., Relative Visual Direction as a Factor in Depth Perceptions in Complex Situations. Project 6-95-20-001, Report 148. Army Medical Research Lab., Fort Knox, Ky. July 1954.

8-178 Gogel, W. C., Tammaro, J. P., and Inaba, K., The Tendency to See Objects as Equidistant and its Inverse Relation to Lateral Separation. Project 6-95-20-001, Report 146. Army Medical Research Lab., Fort Knox, Ky. April 1954.

8-179 Gogel, W. C., Tammaro, J. P., Nordling, D. A., and Nungesser, F. L., Jr., The Perception of the Relative Depth Position of Objects as a Function of Other Objects in the Field of View. Project No. 6-95-20-001, Report No. 107. Army Medical Research Lab., Fort Knox, Ky. January 1953.

8-180 Graham, C. H., "Visual Perception." In: Handbook of Experimental Psychology. S. S. Stevens (Editor). John Wiley and Sons, New York, N. Y. 1951.

8-181 Graham, C. H., "Visual Space Perception." Fed. Proc. Amer. Soc. Exp. Biol. Vol. 2. 1943. pp. 115-122.

8-182 Graham, C. H., Baker, K. E., Hecht, M., and Lloyd, V. V., "Factors Influencing Thresholds for Monocular Movement Parallax." J. Exp. Psychol. Vol. 38. 1948. pp. 205-223.

8-183 Graham, C. H., and Bartlett, N. R., "The Relation of Size of Stimulus and Intensity in the Human Eye: III. The Influence of Area on Foveal Intensity Discrimination." J. Exp. Psychol. Vol. 27. 1940. pp. 149-159.

8-184 Graham, C. H., Brown, R. H., and Smith, J. R., "Brightness Discrimination for Varying Durations of the Just Discriminable Increment." Psychol. Record. Vol. 1 1937. pp. 229-223.

8-185 Graham, C. H., and Cook, C., "Visual Acuity as a Function of Intensity and Exposure-Time." Amer. J. Psychol. Vol. 49. 1937. pp. 654-661.

8-186 Graham, C. H., and Hunter, W. S., "Thresholds of Illumination for the Visual Discrimination of Direction of Movement and for the Discrimination of Discreteness." J. Gen. Psychol. Vol. 5. 1931. pp. 178-190.

8-187 Graham, C. H., and Kemp, E. H., "Brightness Discrimination as a Function of the Duration of the Increment in Intensity." J. Gen. Physiol. Vol. 21. 1938. pp. 635-650.

8-188 Grant, V. W., "Accommodation and Convergence in Visual Space Perception." J. Exp. Psychol. Vol. 31. 1942. pp. 89-104.

8-189 Gruber, H. E., "The Relation of Perceived Size to Perceived Distance." Amer. J. Psychol. Vol. 67. 1954. pp. 411-426.

8-190 Guilford, J. P., Psychometric Methods. Second Edition. McGraw-Hill Book Co., New York, N. Y. 1954.

8-191 Hall, F. G., Visual Disturbances Following Simulated Ascent in Low-Pressure Chamber. U. S. Army Air Forces, Materiel Center Exp. Engng. Sect. July 15, 1942.

8-192 Halsey, R., and Chapanis, A., "On the Number of Absolutely Identifiable Spectral Hues." J. Opt. Soc. Amer. Vol. 41. 1951. pp. 1057-1058.

8-193 Halstead, W. C., "Chronic Intermittent Anoxia and Impairment of Peripheral Vision." Science. Vol. 101. June 15, 1945. pp. 615-616.

8-194 Hammer, E. R., "Temporal Factors in Figural After-Effects." Amer. J. Psychol. Vol. 62. July 1949. pp. 337-354.

8-195 Hardy, L. H., "Investigation of Visual Space." A. M. A. Arch. Ophthal. Vol. 42. 1949. pp. 551-561.

8-196 Hardy, L. H., Rand, G., and Rittler, M. C., "Investigation of Visual Space: The Blumenfeld Alleys." A.M.A. Arch. Ophthal. Vol. 45. January 1951. pp. 53-63.

8-197 Harper, R. S., and Boring, E. G., "Cues." Amer. J. Psychol. Vol. 61. January 1948. pp. 119-123.

8-198 Hattwich, R. G., "Dark Adaptation to Intermediate Levels and to Complete Darkness." J. Opt. Soc. Amer. Vol. 44. March 1954. pp. 223-228.

8-199 Hecht, S., "Diagnosis and Incidence of Vitamin A Deficiencies." J. Conn. State Med. Soc. Vol. 3. No. 5. 1939.

8-200 Hecht, S., "The Instantaneous Visual Threshold after Light Adaptation." Proc. Nat. Acad. Sci. Wash. Vol. 23. 1937. pp. 227-233.

8-201 Hecht, S., "Visual Acuity and Illumination." Arch. Ophthal. Vol. 57. 1928. pp. 564-573.

8-202 Hecht, S., Haig, C., and Wald, G., "The Dark Adaptation of Retinal Fields of Different Size and Location." J. Gen. Physiol. Vol. 19. 1935. pp. 321-339.

8-203 Hecht, S., Hendley, C. D., and Frank, S., The Effect of Anoxia on Visual Contrast Discrimination. U. S. National Research Council, Committee on Aviation Medical Report No. 184. August 15, 1943.

8-204 Hecht, S., Hendley, C. D., Schlaer, S., and Frank, S., Contrast Discrimination Charts for Demonstrating the Effect of Anoxia on Vision. U. S. National Research Council, Committee on Aviation Medicine Report No. 358. August 22, 1944.

8-205 Hecht, S., and Mandelbaum, J., "The Relation between Vitamin A and Dark Adaptation. J. Amer. Med. Assoc. Vol. 112. 1939. pp. 1910-1916.

8-206 Hecht, S., Ross, S., and Mueller, C. G., "The Visibility of Lines and Squares at High Brightness." J. Opt. Soc. Amer. Vol. 37. 1947. pp. 500-507.

8-207 Hermans, T. G., "The Perception of Size in Binocular, Monocular and Pin-hole Vision." J. Exp. Psychol. Vol. 27. 1940. pp. 203-207.

8-208 Herrick, R. M., Foveal Luminance Discrimination as a Function of the Duration of the Decrement or Increment in Luminance. WADC Tech. Report 54-463. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. October 1954.

8-209 Hick, W. E., The Threshold for Sudden Changes in the Velocity of a Seen Object. Great Britain Medical Research Council, Applied Psychology Research Unit, A.P.U. 88 Psychological Lab., Cambridge, MRC 48/472. September 1948.

8-210 Hillmann, B., Lee, G. B., and Sperling, H. G., Brightness Thresholds as a Function of Target Contrast and Retinal Position. Project NM 002 014.09.04, Report 266. U. S. Naval Medical Research Lab., New London, Conn. July 1955.

8-211 Hirsch, M. J., and Weymouth, F. W., "Distance Discrimination. V. Effect of Motion and Distance of Targets on Monocular and Binocular Distance Discrimination." J. Aviat. Med. Vol. 18. 1947. pp. 594-600.

8-212 Hirsch, M. J., and Weymouth, F. W., "Distance Discrimination. VI. Relationship of Visual Acuity to Distance Discrimination." J. Aviat. Med. Vol. 19. 1948. pp. 56-58.

8-213 Hulin, W. S., and Katz, D., "Eye Movements and the Phi-Phenomenon." Amer. J. Psychol. Vol. 46. April 1934. pp. 332-334.

8-214 Hurvich, L. M., and Jameson, D., "Spectral Sensitivity of the Fovea. I. Neutral Adaptation." J. Opt. Soc. Amer. Vol. 43. June 1953. pp. 485-494.

8-215 Hurvich, L. M., and Jameson, D., "Spectral Sensitivity of the Fovea. III. Heterochromatic Brightness and Chromatic Adaptation." J. Opt. Soc. Amer. Vol. 44. March 1954. pp. 213-222.

8-216 Ikeda, H., and Obonai, T., "Studies in Figural After-Effects (IV). The Contrast Confluence Illusion of Concentric Circles and the Figural After-Effect." Jap. Psychol. Research. Vol. 2. 1955.

8-217 Imus, H. A., The Influence of "Adaptinol" and Vitamin A on Night Vision. Tech. Report ONRL-73-52. Office of Naval Research, American Embassy, London, England. July 1952.

8-218 Jameson, D., and Hurvich, L. M., "A Psychophysical Study of White. II. Neutral Adaptation. Area and Duration as Variants." J. Opt. Soc. Amer. Vol. 41. August 1951. pp. 528-536.

8-219 Jensen, E. M., Reese, E. P., and Reese, T. W., "The Subitizing and Counting of Visually Presented Fields of Dots." J. Psychol. Vol. 30. 1950. pp. 363-392.

8-220 Jones, E. E., and Bruner, J. S., "Expectancy in Apparent Visual Movement." Brit J. Psychol. Vol. 45. 1954. pp. 157-165.

8-221 Judd, D. B., "Basic Correlates of the Visual Stimulus." In: Handbook of Experimental Psychology. S. S. Stevens (Editor). John Wiley and Sons, New York, N. Y. 1951.

8-222 Katz, M. S., Morris, A., and Dimmick, F. L., Effect of Various Durations of Red Adaptation on the Course of Subsequent Dark Adaptation. Medical Research Lab., U. S. Naval Submarine Base, New London, Conn. Report No. 1, BuMed Project NM003041.56, MRL Report No. 246. April 27, 1954.

8-223 Katz, M. S., and Schwartz, I., "New Observations of the Pulfrich Effect." J. Opt. Soc. Amer. Vol. 45. No. 7. July 1955. pp. 523-525.

8-224 Keil, F. C., The Effects of Low Barometric Pressure on the Field of Vision. Project 158, Report 1. Army Air Force School of Aviation Medicine, Randolph Field, Texas. June 1943.

8-225 Keil, F. C., Jr., The Effect of Oral Doses of Hyoscine (Scopolamine) on Visual Efficiency. Project 157, Report 1. Army Air Force School of Aviation Medicine, Randolph Field, Texas. June 1943.

8-226 Keil, F. C., Sulpha Drugs and Dark Adaptation. Project 91, Report 1. Army Air Force School of Aviation Medicine, Randolph Field, Texas. November 1942.

8-227 Keller, M., "The Relation between the Critical Duration and Intensity in Brightness Discrimination." J. Exp. Psychol. Vol. 2? May 1941. pp. 407-418.

8-228 Kendricks, E. J., Strughold, H., Haber, H., and Gerathewohl, S. J., Medical Problems of Space Flight. A Special Report, USAF School of Aviation Medicine, Air University, Randolph Field, Texas. August 1955.

8-229 Kinney, J. A. S., "Sensitivity of the Eye to Spectral Radiation at Scotopic and Mesopic Intensity Levels." J. Opt. Soc. Amer. Vol. 45. July 1955. pp. 507-514.

8-230 Klein, G. S., "The Relation between Form and Motion Acuity in Parafoveal and Peripheral Vision and Related Phenomena. Arch. Psychol. Vol. 39. 1942.

8-231 Landis, C., An Annotated Bibliography on Flicker Fusion Phenomena Covering the Period 1940-1952. Armed Forces-National Research Council Vision Committee. June 1953.

8-232 Landis, C., "Determinants of the Critical Flicker-Fusion Threshold." Psychol. Rev. Vol. 34. No. 2. April 1954. pp. 259-286.

8-233 Lanier, L. H., and Tresselt, M. E., A Factorial Analysis of Depth Perception Tests. U.S. Army, Adjutant General's Office, Contract WSW-2496 with New York University, Psychological Research Center. 1950.

8-234 Lee, R. H., Determination on the Effect on Dark Adaptation of Varying Intensities of Illumination in Ready Rooms. USN Medical Research Institute Report No. 1, Research Project X-162. June 1943.

8-235 Lee, R. H., Pijoan, M., Catchpole, H. R., and Finch, E. M., Periodic Fluctuations and Threshold Levels in Dark Adaptation and the Effects Produced by Paredrine, Oxygen, Carbon Dioxide, and Ascorbic Acid. U. S. Naval Medical Research Institute, Research Project X-211, Report No. 2. September 12, 1944.

8-236 Leibowitz, H., "Effect of Reference Lines on the Discrimination of Movement." J. Opt. Soc. Amer. Vol. 45. No. 10. October 1955. pp. 829-830.

8-237 Leibowitz, H. W., "The Relation between the Rate Threshold for the Perception of Movement and Luminance for Various Durations of Exposure." J. Exp. Psychol. Vol. 49. No. 3. 1955. pp. 209-214.

8-238 Leibowitz, H. W., and Lomont, J. F., The Effect of Grid Lines in the Fiew of View upon Perception of Motion: One of a Series of Reports on Perception of Motion. WADC Tech. Report 54-201. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. March 1954.

8-239 Leibowitz, H. W., and Lomont, J. F., The Effect of Luminance and Exposure Time upon Perception of Motion: One of a Series of Reports on Perception of Motion. WADC Tech. Report 54-76. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. March 1954.

8-240 Leibowitz, H., Mote, F. A., and Thurlow, W. R., "Simultaneous Contrast as a Function of Separation between Test and Inducing Fields." J. Exp. Psychol. Vol. 46. 1953. pp. 453-456.

8-241 Lit, A., "The Magnitude of the Pulfrich Stereophenomenon as a Function of Binocular Differences of Intensity at Various Levels of Illumination." Amer. J. Psychol. Vol. 62. 1949. pp. 159-181.

8-242 Lit, A., and Hyman, A., "The Magnitude of the Pulfrich Stereophenomenon as a Function of Distance of Observation." Amer. J. Optom. and Arch. Amer. Acad. Optom., Monograph 122. November 1951. pp. 1-17.

8-243 Livingston, P. C., The Influence upon Night Vision of Artificial Dilation of the Pupil. Great Britain. Flying Personnel Research Committee Report No. 369. OSRD Liaison Office Ref. No. WAM-87-4. October 1941.

8-244 Livingston, P. C., Report on Effects of Anoxia Carbon Monoxide Diabetes or the Field of Vision. Great Britain. Flying Personnel Research Committee Report No. 451. OSRD Liaison Office Ref. No. WAM-153-7. June 1942.

8-245 Lloyd, V. V., "A Comparison of Critical Fusion Frequencies for Different Areas in the Fovea and Periphery." Amer. J. Psychol. Vol. 65. 1952. pp. 346-357.

8-246 Lloyd, V. V., "The Interaction of Stimulus Area and Intensity as Cues in the Perception of Distance." J. Gen. Psychol. Vol. 49. 1953. pp. 167-183.

8-247 Lothridge, C. D., "Stereoscopic Settings as Functions of Vertical Disparity and Target Declination." J. Gen. Psychol. Vol. 49. 1953. pp. 241-260.

8-248 Low, F. N., "The Development of Peripheral Visual Acuity during the Process of Dark Adaptation." Amer. J. Physiol. Vol. 146. 1946. pp. 622-629.

8-249 Lowry, E. M., "The Effect of Hue on Dark Adaptation." J. Opt. Soc. Amer. Vol. 33. 1943. pp. 619-620.

8-250 Luchins, A. S., "The Autokinetic Effect in Central and Peripheral Vision." J. Gen. Psychol. Vol. 50. 1954. pp. 39-44.

8-251 Luchins, A. S., "The Autokinetic Effect and Gradations of Illumination of the Visual Field." J. Gen. Psychol. Vol. 50. 1954. pp. 29-37.

8-252 Luchins, A. S., "The Relation of Size of Light to Autokinetic Effect." J. Psychol. Vol. 38. 1954. pp. 439-452.

8-253 Ludvigh, E., "Determination and Significance of the Photopic Retinal Visibility Curve." Arch. Ophthal. Vol. 24. 1940. pp. 168-181.

8-254 Ludvigh, E., "Determination and Significance of the Scotopic Retinal Visibility Curve." Arch. Ophthal. Vol. 20. 1938. pp. 713-725.

8-255 Lyle, T. K. et al., Effects of Administration of Vitamin A, Ascorbic Acid, and Riboflavin to RAF Personnel. Great Britain. Flying Personnel Research Committee Report No. 473. OSRD No. W-308-4t. July 1942.

8-256 Macworth, N. H., and Winson, F. H., Effects of Benzedrine Sulphate on a Visual Vigilance Test. Great Britain. Medical Research Council, Applied Psychology Research Unit. APU 72, Psychological Lab., Cambridge, R.N.P. 47/401. O.E.S. 129. September 1947.

8-257 Marquez, "La Vision Stereoscopique sans Stereoscope; Fusion et Relief." Bull. Soc. Franc. Ophthal. Vol. 52. 1939. pp. 241-253.

8-258 Matthews, B. H. C., and Luczak, A. K., Some Factors Influencing Dark Adaptation. Great Britain. Flying Personnel Research Committee Report No. 577. June 1944.

8-259 Mayou, B., Visual Problems in Connection with Airsickness. Great Britain. Flying Personnel Research Committee Report No. 464, OSRD Liaison Office Ref. No. WAM-153-20. May 1942.

8-260 McFarland, R. A., and Forbes, W. H., "The Effects of Variations in the Concentration of Oxygen and of Glucose on Dark Adaptation." J. Gen. Physiol. Vol. 24. 1940. pp. 69-98.

8-261 McFarland, R. A., Halperin, M. H., and Niven, J. I., "Visual Thresholds as an Index of Physiological Imbalance During Anoxia." Amer. J. Physiol. Vol. 142. 1944. pp. 328-349.

8-262 McFarland, R. A., Halperin, M. H., and Niven, J. I., "Visual Thresholds as an Index of the Modification of the Effect of Anoxia by Glucose." Amer. J. Physiol. Vol. 144. 1945. pp. 378-388.

8-263 McFarland, R. A., Halperin, M. H., and Niven, J. I., "Visual Thresholds as an Index of Physiological Imbalance during Insulin Hypoglycemia." Amer. J. Physiol. Vol. 165. 1946. pp. 299-313.

8-264 McFarland, R. A., Hurvich, L. M., and Halperin, M. H., "The Effect of Oxygen Deprivation on the Relation between Stimulus Intensity and the Latency of Visual After-Images." Amer. J. Physiol. Vol. 140. 1943. pp. 354-366.

8-265 McFarland, R. A., Roughton, F. J., Halperin, M. H., and Niven, J. I., "The Effects of Carbon Monoxide and Altitude on Visual Thresholds." J. Aviat. Med. Vol. 15. 1944. pp. 381-394.

8-266 McIntosh, B. B., Milton, J. L., and Cole, E. L., Pilot Performance during Extended Periods of Instrument Flight. AF Tech. Report 6725. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. May 1952.

8-267 Mead, L. C., "The Influence of Size of Test Stimuli, Interpupillary Distance and Age on Stereoscopic Depth Perception." J. Exp. Psychol. Vol. 33. 1943. pp. 148-158.

8-268 Mercier, A., and Duguet, Jr., Physiopathology of the Flyer's Eye. USAF School of Aviation Medicine, Randolph Air Force Base, Texas. c. 1948.

8-269 Morin, R. E., Grant, D. A., and Nystom, C. O., Temporal Predictions of Motion Inferred from Intermittently Viewed Light Stimuli. WADC Tech. Report 54-69. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. January 1954.

8-270 Mowbray, G. H., and Gebhard, J. W., "Differential Sensitivity of the Eye to Intermittent White Light." Science. Vol. 121. No. 3136. February 4, 1955. pp. 173-175.

8-271 Mueller, C. G., and Lloyd, V. V., "Stereoscopic Acuity for Various Levels of Illumination." Proc. Nat. Acad. Sci., Washington, D. C. Vol. 34. 1948. pp. 223-227.

8-272 Munster, C., "Ueber den Einfluss von Helligkeitsunterschieden in Beiden Augen auf die Stereoskopische Wahrnehmung." Z. Sinnesphysiol. Vol. 69. 1941. pp. 245-260.

8-273 Noonan, T. R., Dark Adaptation. U. S. Army Air Forces, Materiel Div., Experimental Engineering Sect. February 14, 1942.

8-274 Ogle, K. N., "Basis of Stereoscopic Vision." Arch. Ophthal. Vol. 52. 1954. pp. 197-210.

8-275 Ogle, K. N., "Association between Aniseikonia and Anomalous Binocular Space Perception." Arch. Ophthal. Vol. 30. 1943. pp. 54-64.

8-276 Ohwaki, Y., and Onizawa, T., "The Function of the Ground as 'Frame-Work' in the Perception of Size." Tohoku Psychologica Folia, Tomus XII, Fasciculus 3-4, 53-66. (Tohoku University, Sendai, Japan) 1951.

8-277 Oldfield, R. C., "Apparent Fluctuations of a Sensory Threshold." Quart. J. Exp. Psychol. Vol. 7. Part 3. August 1955. pp. 101-115.

8-278 Palmer, C. E., "The Dark Adaptation Test for Vitamin A Deficiency." Amer. J. of Public Health. Vol. 29. 1939. pp. 309-315.

8-279 Pascal, J. I., "Parallactic Angle in Binocular Space Perception." Arch. Ophthal. Vol. 28. 1942. pp. 258-262.

8-280 Piaget, J., and Lambercier, M., "La Comparaison Visuelle des hauteurs a Distances Variables dans le Plan Fronto-Parallele." Arch. Psy. Geneve. Vol. 29. 1942-43. pp. 173-254.

8-281 Pinson, E. A., Effect of Altitude on Dark Adaptation. U. S. Army Air Forces, Materiel Div., Experimental Engineering Sect. October 7, 1941.

8-282 Pinson, E. A., Test for Demonstration of the Effects of Anoxia on Vision. U. S. Army Air Forces, Materiel Center, Engineering Div., Aero Medical Lab. January 12, 1943.

8-283 Pinson, E. A., and Chapanis, A., The Effect of Moderate Anoxia on Contrast Sensitivity at Low Levels of Illumination. U. S. Army Air Forces, Materiel Center, Engineering Div. August 6, 1943.

8-284 Pollock, W. T., and Chapanis, A., "The Apparent Length of a Line as a Function of its Inclination." Quart. J. Exp. Psychol. Vol. 4. November 1952. pp. 170-178.

2-285 Poulton, E. C., The Effect on Performance of Breathing Pure Oxygen at Atmospheric Pressure for a Short Period. Great Britain. Medical Research Council, Appl. Psychol. Research Unit, A.P.U. 203/53., Cambridge. October 1953.

2-286 Ratoosh, P., and Graham, C. H., "On Interposition as a Cue for the Perception of Distance." Proc. Nat. Acad. Sci., Washington, D. C. Vol. 35. No. 5. May 1949. pp. 257-259.

8-287 Reed, J. B., The Speed and Accuracy of Discriminating Differences in Hue, Brilliance, Area, and Shape. Tech. Report SDC-131-1-2. Mt. Holyoke College, So. Hadley, Mass. September 1951.

8-288 Reid, D. D., "Visual Tests of Fatigue in Operational Flying." Brit. J. Soc. Med. Vol. 3. July 1949. pp. 101-109.

8-289 Richards, W. J., "The Effect of Alternating Views of the Test Object on Vernier and Stereoscopic Acuities." J. Exp. Psychol. Vol. 42. 1951. pp. 376-383.

8-290 Riopelle, A. J., and Hake, H. W., "Area-Intensity Relations in Scotopic Vision Using Annular Stimuli." J. Exp. Psychol. Vol. 42. July 1951. pp. 54-58.

8-291 Robinson, E. J., and Coules, J., An Experimental Study of the Effect of Photometric Brightness on the Judgment of Distance and Size. Contract AF 33(616)432, Tech. Note 103. Boston University, Optical Research Lab., Boston, Mass. September 1953.

8-292 Roscoe, S. N., and Hasler, S. G., Flight by Periscope, Technical Report on Human Engineering System Studies. Contract N6ori-71, T.O. 16, Tech. Report No. SDC 71-16-9. 1952.

8-293 Rose, H. W., "Monocular Depth Perception in Flying." J. Aviat. Med. Vol. 23. 1952. pp. 242-245.

8-294 Ross, S., Hussman, T. A., and Andrews, T. G.,"Effects of Fatigue and Anxiety on Certain Psychomotor and Visual Functions." J. Appl. Psychol. Vol. 38. 1954. pp. 119-125.

8-295 Rouse, R. O., "Color and the Intensity-Time Relation." J. Opt. Soc. Amer. Vol. 42. September 1952. pp. 626-630.

8-296 Rowland, L. S., Sulfa Drugs and Dark Adaptation. Project 91. Report 2. School of Aviation Medicine, Randolph Field, Texas. December 1942.

8-297 Rowland, W. M., The Effect of Sulfathiazole and Sulfadiazine on Visual Fields, Ocular Motility, and Depth Perception. Project 99, Report 1. AAF School of Aviation Medicine, Randolph Field, Texas. December 1942.

8-298 Rowland, W. M., and Sloan, L. L., "The Relative Merits of Red and White Light of Low Intensity for Adapting the Eyes to Darkness." J. Opt. Soc. Amer. Vol. 34. 1944. pp. 601-604.

8-299 Schaefer, K., and Carey, C. R., Influence of Exposure to Various Carbon Dioxide Concentrations on Flicker Fusion Frequency and Alpha Blocking. U. S. Naval Submarine Base, New London, Conn. Medical Research Lab. Report No. 251. August 27, 1954.

8-300 Schlosberg, H., "A Note on Depth Perception, Size Constancy, and Related Topics." Psychol. Rev. Vol. 57. No. 5. September 1950. pp. 314-317.

8-301 Schlosberg, H., "Stereoscopic Depth from Single Pictures." Amer. J. Psychol. Vol. 54. 1941. pp. 601-605.

8-302 Scobee, R. G., and Chinn, H. I., The Effect of Carbon Monoxide on Night Visual Efficiency. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. Project No. 234, Report No. 1. January 26, 1944.

8-303 Senders, V. L., "Visual Resolution with Periodically Interrupted Light." J. Exp. Psychol. Vol. 39. 1949. pp. 453-465.

8-304 Sheard, C., "Dark Adaptation: Some Physical, Physiological, Clinical, and Aeromedical Considerations." J. Opt. Soc. Amer. Vol. 34. 1944. pp. 4[illegible]-508.

8-305 Sheard, C., Brown, J. W., and Wilson, K. G., U. S. Mayo Aero-Medical Unit, Rochester, Minn. June 15, 1942. (CONFIDENTIAL)

8-306 Shlaer, S., "The Relation between Visual Acuity and Illumination." J. Gen. Physiol. Vol. 21. 1937. pp. 165-188.

8-307 Shlaer, S., Smith, E. L., and Chase, A. M., "Visual Acuity and Illumination in Different Spectral Regions." J. Gen. Physiol. Vol. 25. 1942. pp. 553-569.

8-308 Simonson, E., and Brozek, J., Flicker Fusion Frequency: Background and Applications. USAF School of Aviation Medicine. Report No. 2. 195[illegible].

8-309 Simson, E., Brozek, J., and Keys, A., "Effect of Meals on Visual Performance and Fatigue." J. Appl. Physiol. Vol. 1. 1948. pp. 270-278.

8-310 Simson, E., and Winchell, P., "Effect of High Carbon Dioxide and of Low Oxygen Concentration on Fusion Frequency of Flicker." J. Appl. Psychol. Vol. 3. 195[illegible] pp. 637-641.

8-311 Skolnick, A., "The Role of Eye Movement in the Autokinetic Phenomenon." J. Exp. Psychol. Vol. 26. April 1940. pp. 373-393.

8-312 Sloan, L. L., and Altman, A., "Factors Involved in Several Tests of Binocular Depth Perception." A.M.A. Arch. Ophthal. Vol. 52. 1954. pp. 524-544.

8-313 Smith, G. M., Seitz, C. P., and Clark, K. B., "Variations in the Angioscotoma in Response to Prolonged Mild Anoxia." J. Aviat. Med. Vol. 17. 1946. pp. 590-595.

8-314 Smith, W. M., "Past Experience and the Perception of Visual Size." Amer. J. Psychol. Vol. 65. July 1952. pp. 389-403.

8-315 Smith, W. M., "Sensitivity to Apparent Movement in Depth as a Function of Stimulus Dimensionality." J. Exp. Psychol. Vol. 43. 1952. pp. 149-155.

8-316 Solomon, R. L., "The Role of Effort in the Performance of a Distance Discrimination." J. Exp. Psychol. Vol. 39. No. 1. February 1949. pp. 73-83.

8-317 Spragg, S. D. S., and Wulfeck, J. W., "The Effect of Immediately Preceding Task Brightness on Visual Performance." J. Appl. Psychol. Vol. 39. 1955. pp. 237-243.

8-318 Steinhardt, J., "Intensity Discrimination in the Human Eye. I. The Relation of ΔI/I to I. J. Gen. Physiol. Vol. 20. 1936. pp. 185-209.

8-319 Stewart, C. P., Effect of Vitamin Administration on Dark Adaptation. Great Britain. Flying Personnel Research Committee Report No. 62. October 2, 1939.

8-320 Stiles, W. S., and Smith, T., A Mean Scotopic Visibility Curve. Great Britain. Dept. of Scientific and Industrial Research., Nat. Physical Lab., Proc. of the Physical Society. Vol. 56. 1944. pp. 251-255.

8-321 Sutherland, N. S., "Figural After-Effects, Retinal Size, and Apparent Size." Quart. J. Exp. Psychol. Vol. 6. 1954. pp. 35-44.

8-322 Switzer, R. E., The Human Side of Aircraft Accidents. Publ. M-36. A Presentation by Medical Safety Div., Flying Safety Officers. Directorate of Flight Safety Research, Norton Air Force Base, Calif. October 1951.

8-323 Taubman, R. E., "Studies in Judged Number: II. The Judgment of Visual Number." J. Gen. Psychol. Vol. 43. 1950. pp. 195-219.

8-324 Taylor, F. V., "Change in Size of the After-Image Induced in Total Darkness." J. Exp. Psychol. Vol. 29. July 1941. pp. 75-80.

8-325 Teichner, W. H., Kobrick, J. L., and Dusek, E. R., "Commonplace Viewing and Depth Discrimination." J. Opt. Soc. Amer. Vol. 45. 1955. pp. 913-920.

8-326 Teichner, W. H., Kobrick, J. L., Wehrkamp, R. F., Effects of Terrain and Observation Distance on Depth Perception. U. S. Army Qm. Res. Dev. Cent. Report No. 228. 1954.

8-327 Thomas, G. J., "The Effect on Critical Flicker Frequency of Interocular Differences in Intensity and in Phase Relations of Flashes of Light." Amer. J. Psychol. Vol. 67. No. 4. December 1954. pp. 632-646.

8-328 Tisdall, F. F., McCreary, J. F., and Pearce, H., Canada, National Research Council of Canada. Assoc. Committee on Aviat. Med. Research. Great Britain. OSRD No. III-I-2235. Proc. 9th Meeting, App. C. (CONFIDENTIAL)

8-329 Tobias, C. A., "Radiation Hazards in High Altitude Aviation." WADC Tech. Report 52-119. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. May 1952.

8-330 Travis, R. C., "The Effect upon Dark Adaptation and Visual Periodicity of Atropin and Homatropin." J. Exp. Psychol. Vol. 9. August 1926. pp. 348-357.

8-331 Trumbull, R., "The Reliability of the Verhoeff Test of Depth Perception." J. Psychol. Vol. 32. 1951. pp. 35-41.

8-332 Uhlaner, J. E., Gordon, D. A., Woods, I. A., and Zeidner, J., "The Relationship between Scotopic Visual Acuity and Acuity at Photopic and Mesopic Brightness Levels." J. Appl. Psychol. Vol. 37. 1953. pp. 223-229.

8-333 Uhlaner, J. E., and Woods, I. A., A Study of the Relation between Photopic and Scotopic Visual Acuity. U. S. Army, Adjutant General's Office, Personnel Research Sect. PRS Report 858. June 1950.

8-334 Van Tuyl, M. C., "Monocular Perception of Distance." Amer. J. Psychol. Vol. 49. 1937. pp. 515-542.

8-335 Vernon, M. D., "The Peripheral Perception of Movement." Brit. J. Psychol Vol. 23. 1932. pp. 200-232.

8-336 Verhoeff, F. H., "A New Theory of Binocular Vision." Arch. Ophthal. Vol. 13. February 1935. pp. 151-175.

8-337 Verplanck, W. S., The Effects of Paredrine on Night Vision Test Performance. U. S. Naval Submarine Base, New London, Conn. Medical Research Lab. May 25, 1944. (CONFIDENTIAL)

8-338 Vollmer, E. P., King, B. G., Fisher, M. B. and Birren, J. E., The Effects of Carbon Monoxide on Three Types of Performance, at Simulated Altitudes of 10,000 and 15,000 feet. U. S. Naval Medical Research Institute. Research Project X-417, Report No. 7. February 27, 1945.

8-339 Wald, G., "The Spectral Sensitivity of the Human Eye." J. Opt. Soc. Amer. Vol. 35. March 1945. pp. 189-196.

8-340 Wald, G., Harper, P. V., Goodman, H. C., and Krieger, H. P., "Respiratory Effects upon the Visual Threshold." J. Gen. Physiol. Vol. 25. July 1942. pp. 891-903.

8-341 Walker, R. Y., "Differences in Judgment of Depth Perception between Stationary and Moving Objects." J. Aviat. Med. Vol. 12. 1941. pp. 218-225.

8-342 Walker, R. Y., "The Superiority of Binocular over Monocular Vision in Depth Perception in Respect to the Vertical or Horizontal Position of the Object." J. Aviat. Med. Vol. 11. 1940. pp. 87-95.

8-343 Walls, G. L., "The Problem of Visual Direction." Amer. J. Optom. and Arch. Acad. Optom., Monograph 117. February, March, and April 1951.

8-344 Walls, G. L., "Factors in Human Visual Resolution." J. Opt. Soc. Amer. Vol. 33. 1943. pp. 487-505.

8-345 Walls, G. L., The Vertebrate Eye and its Adaptive Radiation. Cranbrook Press, Bloomfield Hills, Mich. 1942.

8-346 Warrick, M. J. et all., Effect of Moderate Positive Acceleration on Ability to Read Aircraft-Type Instrument Dials. USAF Air Mat. Comm. Memo Report TSE AA 694, 10. November 1946.

8-347 Wendt, G. R., Studies of Motion Sickness, Vestibular Function and of Psychological and Physiological Effects of Drugs. Final Report. Contract N6ori-126, T.O. 1, Project NR143-060. Office of Naval Research (University of Rochester). June 1954.

8-348 Wentworth, H. A., "A Quantitative Study of Achromatic and Chromatic Sensitivity from the Center to the Periphery of the Visual Field." Psychol. Monographs. Vol. 40 (3). 1930.

8-349 Werner, H., "Binocular Vision - Normal and Abnormal." Arch. Ophthal. Vol. 28. 1942. pp. 834-844.

8-350 Weymouth, F. W., Visual Perception of Distance. U. S. Office of Scientific Research and Development. Committee on Medical Research, Office of Emergency Management, Contract OEMcmr-291. Bimonthly Progress Reports 1-6. April 1, 1943 to December 1, 1943.

8-351 Whiteside, T. C. D., Vision at High Altitude. FPRC 910. RAF Inst. of Aviat. Med. November 1954.

8-352 Wilder, R. M., Nutrition and the Human Eye. Proc. Inst. Med., Chicago, Ill. (Div. of Medicine, Mayo Clinic) Vol. 15. No. 1. January 1944.

8-353 Winchell, P., and Simonson, E., "Effect of the Light: Dark Ratio on the Fusion Frequency of Flicker." J. Appl. Psychol. Vol. 4. 1951.

8-354 Wolf, E., and Zigler, M. J., "Course of Dark Adaptation under Various Conditions of Pre-Exposure and Testing." J. Opt. Soc. Amer. Vol. 45. No. 9. 1955.

8-355 Wolf, E., and Zigler, M. J., "Dark Adaptation Level and Duration of Test Flash." J. Opt. Soc. Amer. Vol. 41. No. 2. 1951. pp. 130-133.

8-356 Wolf, E., and Zigler, M. J., "Dark Adaptation Level and Size of Test Field." J. Opt. Soc. Amer. Vol. 40. 1950. pp. 211-218.

8-357 Wolf, E., and Zigler, M. J., "Location of the Break in the Dark Adaptation Curve in Relation to Pre-Exposure Brightness and Pre-Exposure Time." J. Opt. Soc. Amer. Vol. 44. No. 11. November 1954. pp. 875-879.

8-358 Wulfeck, J. W., Crook, D. J., and McBride, P. I., Studies on Dark Adaptation. Contract AF 30(602)-199. Exper. I and II. Rome Air Development Center, Griffiss Air Force Base, Rome, N. Y. (Tufts College) September 1953.

8-359 Zegers, R. T., "Monocular Movement Parallax Thresholds as Function of Field Size, Field Position, and Speed of Stimulus Movement." J. Psychol. Vol. 26. 1948. pp. 477-498.

8-360 Zeidner, J., An Analysis of Visual Acuity Forms during Dark Adaptation to Various Low Brightness Levels. The Catholic University of America Press, Washington, D. C. (PhD Thesis.) 1954.

8-361 Zoethout, W. D., Physiological Optics. The Professional Press, Inc., Chicago, Ill. 1947.

CHAPTER 9

FACTORS INFLUENCING VISION OUTSIDE THE AIRCRAFT

For some time to come, pilot and crew will depend on direct vision much of the time for taking off, navigating, judging the attitude of their aircraft, detecting and identifying ground objects and other aircraft, flying in formation and refueling in the air, landing, and to some extent fire control.

It is true, of course, that instruments are already better than direct vision in some phases of fire control. They also make satisfactory substitutes (in certain circumstances) in navigating, and maintaining altitude, attitude, and course in bad weather. Nevertheless, direct vision has advantages that are not present in instrument flight. Visual flight is easier and less tiring than instrument flight. The eyes and brain can distinguish between different aircraft, and especially between different objects on the ground, as no radar can. Human vision is less subject to failure than instruments, and it cannot be jammed by the enemy, or disclose position. For these reasons, some means for the pilot to see out of the aircraft is contemplated even in aircraft of such high performance that the canopy must be eliminated.

Visual flight rules (VFR) are set forth in the Civil Air Regulations. VFR conditions are usually expressed in terms of ceiling (height to the base of the clouds) and visibility (horizontal distance to the farthest object that can be seen). Numerous regulations to cover special situations have been written and agreed on by civil and military authorities. In general, when a flight is conducted under VFR, the pilot is able to see at least some portion of the ground, and ambient illumination is usually (though by no means always) higher than in flights conducted under instrument flight rules. Even under VFR, however, conditions are often far from ideal for visual functioning.

Certain variables limit the pilot's vision on any kind of flight -- a simple cross-country flight or a tactical interception, bombing, reconnaissance, or search mission. One source of variables is the pilot's own visual apparatus. Earlier in the book, it was pointed out that there are limits to the fineness of visual discrimination even under the best of circumstances. A second source of variables is provided by the canopy, windshield, and general configuration of the aircraft. Then there are such influencing factors as periscopes, high-altitude helmets and telescopes. Still another source of variables is the state of the sky -- the weather, time of day, type and altitude of clouds, altitude of the aircraft, etc. This chapter explores all of these variables as well as the problems raised by visual illusions.

The effects of vibration on visual performance are discussed briefly in Chapter 13. It should be noted that vibrations apply to vision outside the aircraft as well as inside, but since the discussion on vibrations concerns itself chiefly with instrument reading, it is placed in the chapter on Factors Influencing Vision Within the Aircraft.

VISION THROUGH THE WINDSHIELD AND CANOPY

Windshields and canopies are made of transparent glass or plastic of various shapes and dimensions, supported by metal frames. At best, they obstruct vision to some extent. At worst, they can practically blind the pilot during some phases of flight. Recent evaluations of various aircraft point up the fact that failure to use the best available materials and configuration of windshields and canopies can nullify other improvements in aircraft. Among the visual problems in one fighter aircraft are (1) restricted vision to the rear, (2) poor forward vision due to a "rainbow" effect in the windshield, distortion in the windshield, and the visual obstruction caused by heavy framework, and (3) an ineffective canopy defrosting system.[9-3] In a "hundred series" all-weather interceptor aircraft, the disadvantages are (1) restriction of vision by the framework of the windshield and canopy, (2) distortion through the forward part of the canopy, (3) glare from the shiny metal surfaces of air-inlet ducts on the fuselage on either side of the cockpit, and (4) frosting of the windshield in a rapid descent.[9-2] Finally, visual defects in another hundred series fighter include: (1) a low canopy configuration and some distortion, which restrict forward visibility during landings, and (2) a blind spot immediately behind the aircraft. For this aircraft, it has been recommended that: (1) the poor forward visibility be accepted as a compromise and that special training be given for landing, and (2) the canopy be redesigned to improve rear vision, or combat tactics be adjusted to compensate for poor rearward visibility.[9-1]

In summary, if the field of view is too restricted, performance will be impaired. If the windshield and canopy have poor optical properties, or if cockpit lighting reflects or refracts so as to impair vision through the canopy or windshield, performance will again be impaired. In the remainder of this section, we will consider how much these two factors influence vision, and what can be done about it.

Fields of View from Aircraft

In the following paragraphs, you will find data on the limits of man's field of vision and the effect of angle of view in visual flight. The effects of the field of vision in take-off, navigation, interception, reconnaissance, and avoidance of mid-air collision are discussed under the appropriate headings in this chapter and apply the data presented in Chapter 6.

That data on human vision can help the designer is strikingly illustrated by a consideration of head and eye movements. By moving head and eyes alone, without moving the body, a person can see through an arc of more than 180 degrees to either side of straight ahead; that is, he can scan through a full circle of 360 degrees.[9-16] Of course, it is not easy to scan such a large field of view, nor is it necessary in most situations. Suppose, however, that movements are limited to those that are performed easily and naturally. In this case, the total field obtained by both head and eye movements subtends about 75 percent of the sphere about us (155 degrees to either side, 91 degrees upward, and 112 degrees downward). A pilot could not scan this entire field with his central vision, even if there were no obstructions; in a fast moving aircraft, he might miss objects ahead while scanning to one side. Nevertheless, the entire field is potentially useful in avoiding collision or avoiding attacking aircraft, for example, because an object near the edge of peripheral view creates a vague image; it signals its presence, and can then be identified by turning for complete fixation. The percent of this field available to the pilot has been calculated[9-23] for a number of transport aircraft, on the basis of windshield window measurements. The highest rating represented only 21 percent of the potential visual field, while some windshield areas scored as low as 14 percent. There is, of course, the question of what is an adequate score, but the high number of collisions and near collisions reported in flight shows that an improvement in visibility is highly important.

The Civil Aeronautics Authority has published a set of recommendations on minimum visual angles from cockpits of transport aircraft.[9-12] These standards can also be applied to military transports. They are also of interest because they are based on research[9-11,9-13,9-17,9-21] that serves as a good illustration as to how data can be gathered and analyzed to solve practical problems.

A program to study cockpit visibility was begun in 1948 by the Technical Development and Evaluation Center of the CAA. First a questionnaire was sent to several thousand airline pilots asking them to evaluate vision from transport aircraft and make recommendations on the size and location of windshield openings.[9-21] Second, a binocular strip-film camera was developed which provided a quick and accurate means of measuring and recording cockpit visibility limits in terms of angles of vision. The camera superimposes a grid of horizontal and vertical lines on the negative. It has two lenses spaced at the separation distance of the eyes. Thus, when positioned correctly, it duplicates the pilot's two eyes and records the visual angles where windshield posts and the like obstruct vision for one and for both eyes.[9-11] A sample photograph is shown in Figure 9.1. Third, movies of pilots' eye movements were made to discover where on the windshield the pilot was looking and for how long[9-13] during each phase of visual flight maneuvers. Some of the results of this investigation are discussed in Chapter 12. Fourth, information was gathered on the visual angles required by the pilot to see another aircraft on a collision course.[9-17] Common probable collision courses were selected on the basis of typical maneuvers required in flight. A series of charts and graphs was constructed. The reader can enter them with such items as: (1) the difference in heading between two aircraft on collision courses, (2) the aircraft speeds, and (3) the type of maneuver. He can then read off the visual angles required by the pilot of one aircraft to see the other aircraft at any time prior to collision, at any distance of separation, and at any relative closing speed.

The recommended standards for visibility from the cockpit, based on the four phases of the program, are illustrated in Figure 9.2. In addition, specifications are given for visibility of the horizon during Instrument Landing System approaches, rated-power climbs, and maximum approved bank angles. However, the same techniques might be used to find minimum values for military aircraft. Since there are so many types of military aircraft and missions, specifications should be developed that take into account the maneuvering capability of each type of aircraft and the extremes of flight attitude imposed by the design and the requirements for each type of mission.

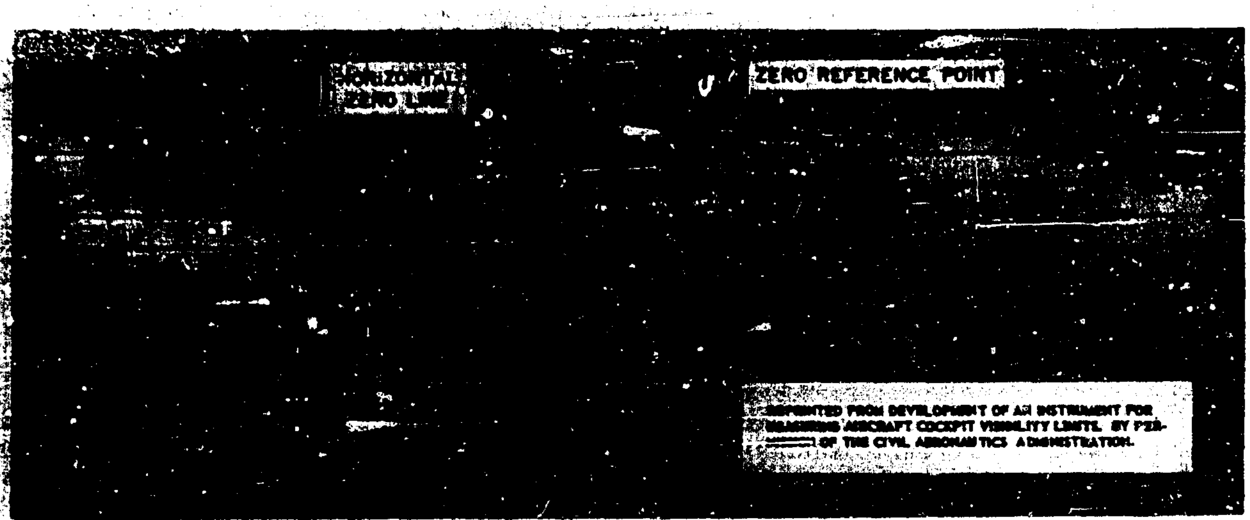


Figure 9.1 Pilot's Field of View From Aircraft Cockpit

Picture was taken with binocular camera simulating eyes. In black areas, vision is obstructed to both eyes, while in gray areas, pilot can see out of cockpit with one eye. Grid lines enable investigator to judge positions of obstructions in visual field. Note how narrow unobstructed field becomes to right, or side of windshield away from pilot. (from Edwards[9-11])

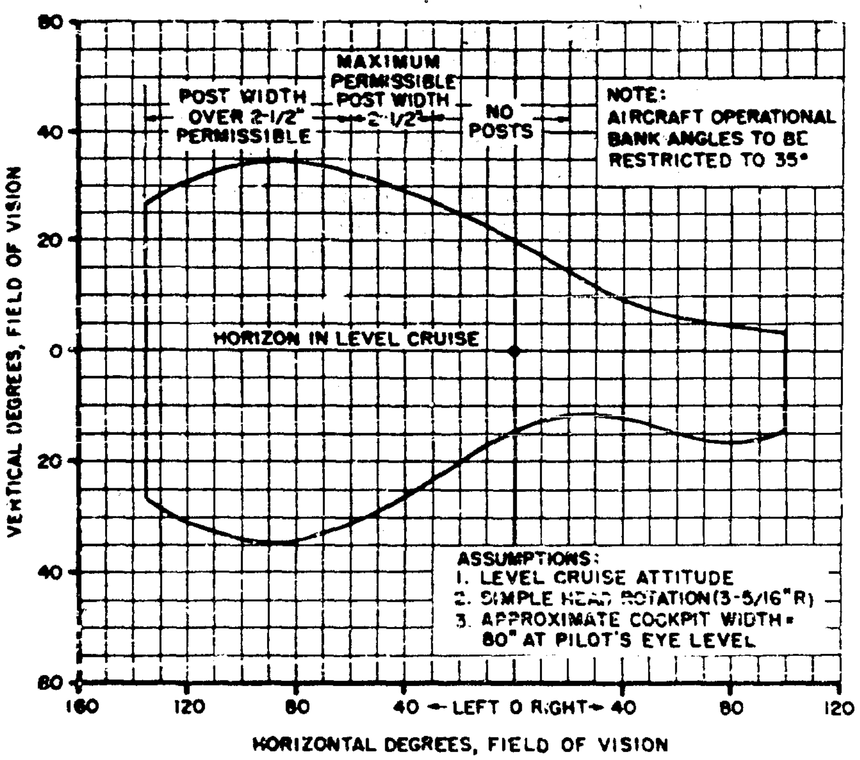


Figure 9.2 Recommended Standards of Visibility From Cockpit of Transport

The pilot should be able to see out of the cockpit without moving his head in the area enclosed by the curves, except where posts wider than 2-1/2 in. are permitted. (Edwards & Howell[9-12])

Design features intended to improve the aerodynamics of high-performance aircraft often reduce the pilot's ability to see out of the cockpit, though some aerodynamic changes improve vision; for example, in many jet aircraft, the pilot has better over-the-side vision than in many propeller-driven aircraft because he is located farther forward of the wings. On the whole, however, better aerodynamics means thicker and more slanted windshields, more sharply curved canopies, and generally poorer vision. Such items as radomes can interfere seriously with over-the-nose and over-the-side vision.

One problem, for example, is the loss of over-the-nose visibility in needle-nose interceptors. The problem is accentuated in the delta-wing configuration during the landing approach because of high angle of attack. Difficulties encountered in such aircraft have led to the recommendation that the pilot should be able to see the runway from 1000 feet ahead on out when on a three-degree glide slope 50 feet over the end of the runway. An unconventional solution to this problem is employed in the current British Fairey "Droop Snoot" fighter, in which the nose section bends down for an increased visibility during landing.

With respect to dimensional requirements in the vertical plane, two researchers[9-22] recommend the following: (1) Forward visibility over the nose should be at least 15 degrees below the horizontal viewing plane of the pilot in flight attitude. (2) Visibility in the after portion of the field of vision should be at least 5 degrees below the horizontal viewing plane. (3) Over-the-side visibility should be no less than 50 degrees below the horizontal except where wings interfere. (4) Structural parts of canopies should be eliminated as far as possible. (5) Cockpit lights, instruments, etc. should not protrude above the fuselage into the transparent sections of canopy and windshield.

Nearly all the other aircraft a pilot sees he sees well forward. In a note on windshield design and visibility from fighter aircraft, it was stated[9-9] that of all aircraft that appear within a pilot's range of vision by day, 84 percent are likely to appear in a 112-degree field ahead (i.e., a field subtending 112 degrees at the eye). Since there is less chance that the windshield will collapse if it is narrow, this study suggests that the aircraft be designed so that the pilot's head is well forward, so that he can see objects at the largest possible angle from straight ahead. This is rather impractical, however, since there must be enough room for instruments and controls.

Structural Members of Windshield and Canopy

Another study[9-20] points out that frames to support the windshield must often be placed within the pilot's field of vision. They suggest that as many of the frames as possible should make apparent angles of about 90 degrees with the mean plane of vision; that is, the planes containing the frames should form right angles with the approximately horizontal plane containing the lines of sight of both eyes when the pilot is looking ahead. Further studies also recommended that the designer make the frames as narrow as he can without having to add more frames.

A structural member of the windshield will block off part of the field of vision for both eyes if it is wider than the distance between the pupils of the eyes[9-14]; that is, if it is so wide that one eye will not "cover" for the other unless the pilot moves his head. The angle subtended by the blind area is proportional to the width of the frame member minus the interpupillary area. These points are illustrated in Figure 9.3. In A, the frame is narrower than the effective interpupillary distance. The left eye can see any part of the field of vision that is blocked for the right eye, and vice versa, except for a narrow triangular area just behind the frame. In B, the frame is just the width of the effective interpupillary distance -- about 2-1/2 inches maximum. It creates a blind area exactly as wide as the interpupillary distance, but the blind area gets no wider out into space; only a 2-1/2 inch strip will be blocked out whether an object is five inches or five miles behind the frame. For practical purposes, in an aircraft, a frame 2-1/2 inches wide therefore does not obstruct vision for both eyes. In C, however, the frame is wider than the interpupillary distance. The effective binocular blind area now increases with distance by a factor proportional to the excess in width over 2-1/2 inches and the distance of one frame member from the eyes; an entire aircraft can be hidden up to a dangerously close distance.

Note that for objects seen to one side or the other of the fore and aft vertical plane bisecting the head, the effective interpupillary distance (Fig. 9.3c) decreases with the cosine of the angle between the line from eyes to object and this plane. In other words, a smaller obstruction to one side will block vision (provided the pilot does not turn his head). Therefore, windshield obstructions should be less than interpupillary distance. To allow a safety factor, they should be well below two inches in width.

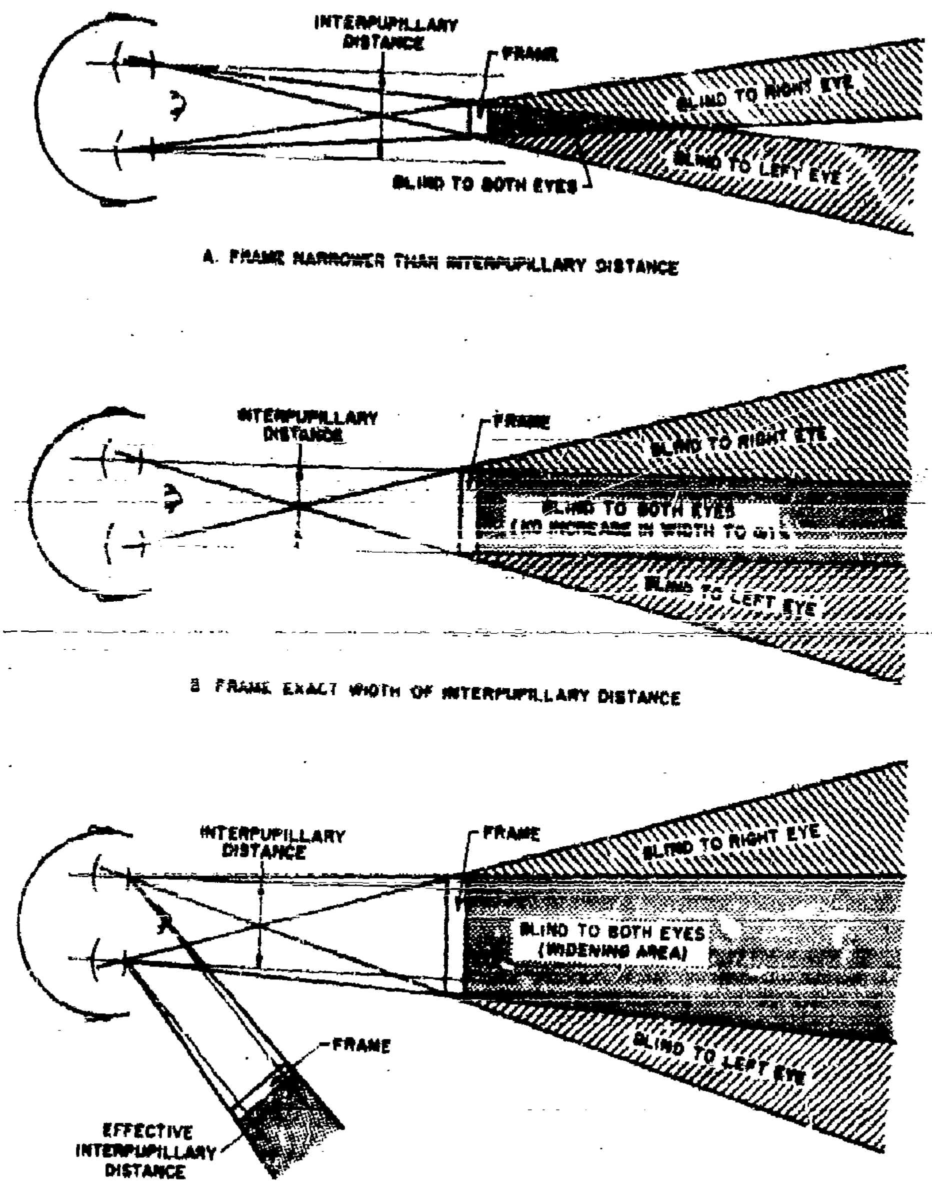


Figure 9.3 Area Blocked by Windshield Frame Member of Less, Same, and Greater Width Than Distance Between Pupils

Note that in B, the blocked strip is the same width out to infinity; thus any object larger than about 2-1/2 inches can be seen with at least one eye. In C, the blocked-out area widens, and large distant objects may be hidden. As the angle from the head's centerline increases, effective interpupillary distance decreases, and a narrow frame blocks out vision.

Design of Transparent Sections in Aircraft

Visual flight performance is affected by the quality and configuration of the transparent sections of the windshield and canopy. Distortions must be kept to a minimum if vision is to be effective. Under most circumstances, transparent sections should also have high light transmission -- they should cut out as little light as possible. Data are presented here on:

1. Loss of vision when looking through transparent material (even when it is of high quality).

2. The effect of specific transparent material and special coatings on vision.

3. Loss of vision when transparent surfaces are dirty or cracked.

4. Curved versus flat transparent surfaces, and the angle of the surface with the line of sight.

5. The effect of time of day and altitude, and the loss of vision due to reflection and glare.

Distortion in Laminated Glass. One team of investigators[9-8] derived mathematical formulas for the extent to which transparent, parallel, plane panels will cause apparent changes in direction, size, shape, and distance of an observed object. They also computed the change that occurs in the angle of parallax for two objects at different distances when a windshield with parallel, plane surfaces is placed between the objects and the eye. (The angle of parallax is the angle between the lines of sight of the two eyes when they are converging on an object. It is a very important cue in distance judgment -- see Chapter 8.) All calculations were made for resurfaced, laminated, bullet-proof, Nesa-coated windshield panels with a thickness of 38.1 mm and a refractive index of 1.5153. It was shown[9-8] that for the rather long distances at which pilots view other aircraft and objects on the ground, the panels caused negligible changes in direction, size and shape. However, they did change the angle of parallax, and hence the apparent distance. Depending on the angle of incidence of the panels, the change in the angle of parallax was as high as ± 30 percent. For an object closer than 10 meters, however, the panels caused significant changes in apparent direction, shape, and size, as well as distance.

Good glass has an inherent deviation error of no more than 3 minutes of arc. This amounts to a deviation of only 10 inches in the line of sight at 1000 feet or 26 feet at 30,000 feet. That is, an object 30,000 feet away will be seen only 26 feet to one side of its true position.[9-22]

Vision Through Plastics. Vision is generally better through glass than through plastic because there is less "optical haze" in glass.[9-22] One investigator[9-18] took plate glass and plastic* in various states of maintenance from the hoods of operational aircraft. In a room with white walls, the panels were set up so that they could be inclined at various angles. Illumination was 140 foot-candles. The test object was a white disc on the wall, 5 inches in diameter, with a gray spot 2 mm in diameter. Brightness contrast between spot and disc was 20 percent. The disc was rotated before each trial, and each of fourteen subjects moved forward until he could state the position of the spot correctly. The range for unobstructed vision was determined and then the range for vision through different pieces of glass and plastic tilted at different angles. The results were expressed as visual range lost when the view was obstructed by glass or plastic.

The results may be summarized as follows:

Table 9.1 Comparison of Loss of Visual Range Due to the Inclination and Material of the Windshield

Angle of Inclination from Sightline	Loss of Visual Range in Percent		
	Plate Glass	Plastic	
		Clean	Dirty
0°	2.4	2.8	7.3
45°	6.7	9.3	16.8
70°	11.0	24.1	39.3
80°	15.6	37.8	48.2

* Transparent acrylic resin produced in sheet or rod form

Vision through clean plastic was thus a little worse than through plate glass when the two were viewed head on, and the difference increased rapidly as the tilting increased over 45 degrees from the vertical. That is, in a windshield slanted more than 45 degrees, the light reflected on the plastic would reduce visual range severely below that attained with glass. Vision was further reduced when the plastic had been on an aircraft for a long time -- when it was dirty and scratched.

The Effect of Conductive Coatings and Bullet-Proofing. Electrical conductive coatings are used on many aircraft windshields and canopies for defogging, defrosting, or the removal of static charges. Unfortunately, conductive coating further reduces light transmission[9-15] Similarly, bullet-proof glass has obvious advantages, but improved vision is not one of them. If polarized light from the sky or from a runway falls upon a hardened glass windshield, a change in plane or polarization may take place. For example, when oblique vision through side windows is used, dark patches may appear in a regular pattern in the field of view. These strain patterns can seriously interfere with visual search. However, they can be avoided by properly designing and testing the windshield before installation. The following procedures are recommended:

1. Incline side panels less than 45 degrees to the line of sight.

2. Whenever an auxiliary plate of glass or plastic is to be incorporated in the windshield, place it on the outboard side of the hardened layer.

3. Examine the complete windshield in a steeply inclined position under incident plane polarized light, without analyzer, before it is installed on the aircraft[9-19]

Detecting and Analyzing Distortions. In the ordinary course of flying, small visual inaccuracies can be tolerated. Large distortions, however, can be expected to cause piloting errors and to annoy and fatigue the pilot generally, particularly after long periods of flight. Aviation personnel object to obvious optical imperfections in aircraft transparencies, such as bull's eyes, crazing, scratching of the surface, and imbedded foreign material that is often mistaken to be distant aircraft. They object to distortions that interfere with visual target detection and reduce their ability to estimate the size, form, and distance of sighted objects. For example, distortions can produce annoying undulations in the contours of sighted objects.

However, while distortion is a recognized evil in transparencies, it is difficult to detect and evaluate because distortion is most disturbing during movement of the eye or sighted object, and this movement is hard to incorporate into objective tests. Perhaps the only practical way to test for distortion is to view or photograph objects through the completed windshield. One method is to photograph a grid through the windshield. In one such test[9-5] a binocular camera simulated pilot's vision. It was placed about where a pilot's eyes would be in relation to the windshield. A grid of 1-inch squares was placed behind the windshield. Distortion in the transparency then made grid lines appear wavy or curved on the photograph and angles between lines appear no longer square. Such photographs both give an over-all picture of windshield distortion and provide a means of measuring the amount of distortion at various points. In evaluating windshields from photographs, two faults were considered most serious: (1) severe local distortions, and (2) distortions affecting a large area of the windshield. The photographic analysis compared moderately well with pilot's preferences. That is, when grids were photographed through windshields that had been tried out by pilots, the ones that were rated as good on the basis of the photographs were also rated as good by the pilots, and the ones that showed excessive distortion on the photographs were considered poor by the pilots.

Curvature and Angle of Windshield. As far as vision is concerned, there is little question that flat panels are superior to curved for windshields and canopies. In one type of jet training aircraft, for example, poor light refraction is reported through part of the curved left section of the windshield[9-4] For side panels, one investigator[9-9] noted that flat glass is better than curved plastic, which latter also has the disadvantage of becoming marred by the weather. The data in Table 9.1 show that vision is best when the line of sight is perpendicular, or nearly so, to the windshield and canopy. Further evidence of this sort comes from other studies[9-22] An aircraft that can be seen a mile away with unobstructed vision can be seen only half a mile away through a piece of dirty plastic that has been set at an angle of about 70 degrees to the line of sight. On the other hand, a poor piece of glass placed perpendicular to the line of sight is much better optically than a very good piece of glass placed at a large angle from the perpendicular -- 40 degrees or more.

In a recent analysis of various transparent surfaces used for windshields, canopies, and visors [9-15], tests were conducted to determine the ability of aircrew to discern an object against its background at various brightness contrasts. On the basis of these tests, standards were set up for the minimum amount of light a transparency should transmit and the maximum amount of haze it should be allowed to contribute at various angles in respect to the line of sight. The tests were conducted under illuminations corresponding to the range from daylight to darkest night. The Luckiesh-Moss low-contrast test chart was used. It has test numerals whose contrast with the white background ranges from 3.9 percent to 37.0 percent. The chart was viewed at a distance of five feet. Visual contrast threshold values measured through the various transparencies were compared with values obtained with unobstructed vision. A maximum-contrast, variable-sized test object was also used. It was a narrow target 24 inches long, whose width could be varied from zero to three inches by varying its tilt. The target was painted dull black against white. It was viewed at a distance of 10 feet. Off-center fixation was used. In setting standards on the basis of these tests, consideration was given to the initial optical properties of the transparent materials to the windshield angle of incidence, and the visibility requirements for night flying. The results are shown in Table 9.2. In each instance the lower permissible limit is given for light transmission and the higher permissible limit for haze values. Haze, in this instance, refers to light scattering within the transparent materials.

Table 9.2 Standards for Light Transmission and Haze, in Percent

	Windshields (Incidence Angle)*				Canopies	Visors
	55°	60°	65°	70°		
<u>Highly desirable</u>						
Transmission	71	74	83	99	89	90
Haze	0.5	0.5	0.5	0.5	0.5	0.5
<u>Acceptable</u>						
Transmission	66	69	78	93	83	83
Haze	1	1	1	1	1	1
<u>Minimum value</u>						
Transmission	64	67	75	89	77	79
<u>Maximum value</u>						
Haze	2	2	2	2	2	2

*The incidence angle is the angle the light from the object viewed (and also the line of sight) makes with a line perpendicular to the transparent surface.

A loss in light transmission through a windshield or canopy is obviously most serious when objects are dim, as at night. The present trend among aircraft designers to slope windshields at steeper angles for aerodynamic reasons reduces the amount of light transmitted below acceptable levels for some night vision requirements [9-15]. An angle of incidence of 65 degrees is specified in several recent windshield designs. At this angle, only 80 percent as much light is transmitted as when the line of sight is normal to the surface [9-15].

<u>Reflection</u>. Light reflected by a windshield or canopy can also interfere with vision. This problem also tends to be more serious at night, when cockpit lights are bright compared to the sky. For example, light reflections in the canopy at night have been a disturbing factor in several jet aircraft [9-4]. In one analysis of cockpit lighting [9-6] it is reported that reflections from interior lights sometimes obstruct vision through the windshield and canopy during night flight. The author suggests that this problem can be reduced by putting appropriate shields on lights and lighted instruments.

Both surfaces of a piece of glass admit and reflect light; light is received from outside the aircraft and "parasite" light is received from inside and outside sources. Both kinds of light are

reflected and absorbed, so that the observer's eye receives filtered light from the outside which is reflected back and forth, producing "ghosts" and doubly reflected parasitic light from inside sources near the pilot. Reflections from the glass surface due to luminous instruments and the like tend to glare or to have a blinding effect[9-6]. These disturbances, however, are most pronounced when (1) the intensity of light transmitted through the windshield from outside is considerably lower than the intensity of the parasite light and (2) the positions of the light sources inside the cockpit, the angle of the glass, and the position of one eye are such that angle of incidence = angle of reflection.

Reflections are a problem not only at night. By day, sunlight and bright flashes of reflected sunlight from the surfaces of the aircraft, from other aircraft, or from bright objects on the ground may enter the cockpit. This light may enter through the canopy and strike the windshield from inside, or vice versa; it may be reflected off objects inside the cockpit; or it may be reflected and refracted back and forth between the surfaces of the glass in the windshield or canopy. In any case, reflections are set up that cause glare or obstruct vision. To meet this problem, one experimenter[9-10] applied a special reflection-reducing coating to the plastic enclosures of SNJ aircraft. Ten pilots then flew SNJ's treated with the coating and SNJ's not treated with it in quick succession. The coating was found to improve pilot visibility from the cockpit enclosure by (1) reducing glare and eyestrain, and (2) reducing the interference with vision caused by reflections and cross-reflections of light on bright objects. This second improvement was particularly noticeable on clear, sunny days, when flash normally causes the greatest difficulty. Flash is undesirable for other reasons also. In wartime, sunlight reflected from a canopy or windshield permits the enemy to spot an aircraft more easily.

Light at High Altitudes. At low altitudes, the sunlight is scattered and diffused to some extent by the atmosphere even on clear, bright days. At the high altitudes where jet aircraft cruise most efficiently, however, the air is so thin that the sun appears as a very bright object in a dark sky; there is little atmospheric scattering. Clouds below the aircraft also serve as a source of excessive brightness at high altitudes. Similarly, an object outside the aircraft -- another aircraft or the surfaces of one's own aircraft -- will appear extremely bright if it is reflecting sunlight directly toward the pilot or observer. In contrast, a nonreflecting object will appear very dim. Thus, a man who is adapted to the bright objects that he sees at high altitude may have great difficulty seeing nonreflecting targets; conversely, a man adapted to dimmer objects may experience discomfort and temporary blinding if a reflecting object comes within his field of vision. Furthermore, oxygen deficiency increases the threshold of brightness discrimination. According to one study[9-7], the brightness contrast of objects at high altitude exceeds the "borderline contrast of comfort and discomfort." Farther on in this chapter, information is presented on natural illumination; this will give the aircraft designer a basis for both lighting and shielding the cockpit for high-altitude flight. Somewhat related to the problems of distortion through windshields[9-5] are distortions in shock waves encountered in the neighborhood of Mach 1. However, numerical calculations show that the deviation of light rays through shock waves under practical conditions amounts to less than one minute of arc. It thus presents a very small problem.[9-8]

PERISCOPES FOR PILOTING AIRCRAFT

Periscopes are indicated as a substitute for windshields to provide outside vision for piloting certain very high-performance aircraft. All periscopes have a restricted field of view, and those using them must learn to use new clues to distance judgment or to attach a different value to clues. Because of these two major disadvantages and several minor ones in comparison with windshields, periscopes are not indicated for slower aircraft.

Requirements for Piloting

Until recently the only means for viewing outside an aircraft was through canopies and windshields. In certain higher performance aircraft it is desirable to eliminate the windshield for aerodynamic and thermodynamic reasons, if another satisfactory means of outside vision can be devised. The aerodynamic interest is to minimize or eliminate drag due to the windshield. This begins to assume importance at higher Mach values, particularly in aircraft that are to have extended range without refueling. The thermodynamic interest is to insulate and refrigerate the cabin against the very high skin temperatures encountered at the higher Mach values, and to make the cabin structurally integrated and otherwise able to stand up under the resulting steep thermal gradients. Also, elimination of a windshield would simplify radiation shielding.

In addition to these reasons, a device for outside viewing gives added flexibility in locating the pilot in the aircraft and in locating the indicators and controls used by the pilot. The pilot must be able to identify certain objects outside the aircraft and judge their position in space, both in respect to the aircraft's axes and in distance; and he must be able to perceive changes in location. The size and location of the field of view he must have to identify and locate depends on the phase of the flight and the aircraft's mission. The flight phases are:

Terminal Phase - (1) Take-off
- (2) Traffic pattern
- (3) Landing

Cruise Phase - (1) Geographical orientation of aircraft
- (2) Avoiding air collision

Strike Phase - Target detection
  Air target detection
    offensive
    defensive
  Ground target detection
    offensive
    defensive

The field of vision required for the cruise and strike phases may be reduced or eliminated by the use of electronic devices.

Great restriction of the visual field may lead to a lack of confidence, uneasiness, or even claustrophobia on the part of the pilot.

If electronic detection devices are not used, the largest field of view is required to avoid air collision. The faster aircraft is ordinarily responsible for detecting and avoiding the other aircraft. A field of nearly 180 degrees in azimuth is required for the faster aircraft. If the slower aircraft were also considered responsible for the search, a field of 360 degrees would be required (so that it could avoid a rear-end collision).

The field needed for air target detection, both offensive and defensive, depends on the speed of the aircraft as well as its mission.

The turning radius of very high-speed fighter aircraft is great; it cannot turn sharply enough to attack aircraft off to the side, and it is in little danger of being attacked by them. Therefore, a more restricted field of view to the front (and in certain cases, to the rear) is permissible.

Within detection ranges, other aircraft are of no concern to the pilot unless they are within a zone shaped roughly like a cone with curved sides ahead of the pilot's aircraft (Fig. 9.4). For purposes of detecting targets and avoiding attack, the useful field of vision need only comprise this cone -- which becomes increasingly narrow with higher airspeeds.

Bombers are concerned only defensively with air targets. Here the useful field is limited to a cone to the rearward, unless the enemy is using a collision course attack or flexible gunnery. However, in bombers, crew members other than pilots generally perform rearward search.

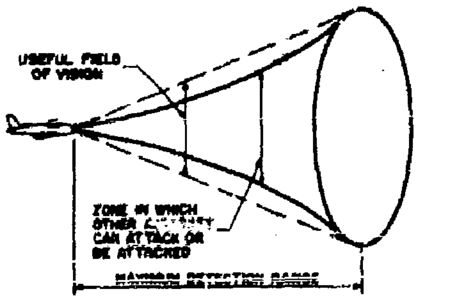


Figure 9.4 Useful Field of Vision, for Purposes of Attacking or Avoiding Attack, for Very High-Speed Fighters

For ground targets, pilots of ground support or reconnaissance aircraft must see downward at a large angle of depression from the horizon. Unless a large angle of depression can be provided forward, of the order of 30° or more, search can be better performed over the side by other aircrew members. Then the pilot's visual field need extend only 12 degrees or 15 degrees below horizon.

For the visual level-attitude type bomber, ground targets are detected by other crewmen than the pilot, so there are no visual field requirements here for ground target detection in periscopes for pilots.

The field requirements for navigation depend on the type of navigation used. In pilotage navigation, things such as atmospheric conditions, the type of check points, and familiarity with the terrain determine the size of the field required. As an estimate, it could be said that 90 degrees on total azimuth would be sufficient in most circumstances.

The visual field requirements for the terminal phase differ according to the operation involved. For the take-off, the field requirements are the least of those in any aircraft operation. On the other hand, flying the conventional traffic pattern requires 180 degrees in azimuth in order to make accurate turns on to the base leg and final approach. In the final approach to flare out, the pilot must be able to see the point of touchdown at all times, to see a sufficient length of the runway, to stay properly oriented with respect to position along the runway, and to have sufficient field in azimuth so that the distance above the runway is easily judged. Then, in the final approach, the pilot must be provided with a field of vision extending downward with respect to the aircraft by an amount that exceeds by a few degrees the maximum nose-up attitude of the aircraft with reference to the runway. The larger the angle in azimuth the greater the ease of vertical distance judgment.

Distance Judgment. The requirements for distance judgment in very high-performance aircraft are approximately the same as in other aircraft, except that these aircraft would generally have higher landing speeds, so that distance judgment would be more critical. Distance judgment can be considered as part of the orientation problem. In the three dimensions there is need for angular orientation about the horizontal, longitudinal, and vertical axes. Orientation about the first two is achieved as long as the horizon is seen. Orientation about the vertical axis is accomplished by reference to the flight instruments. Orientation along the three axes, or translational orientation, with regard to viewed objects, involves distance judgment. Good distance judgment is needed particularly along the longitudinal and vertical axes. The ways in which periscopes affect distance judgment are related in later paragraphs, where the different types of periscopes are described.

Vision While Flying in a Prone Position

To reduce the effects of acceleration in very high-performance aircraft, it has been proposed that the pilot fly in a prone position. Visual problems that would be imposed by the prone position in flight have been studied by several investigators. In one study, ten subjects, while in a prone-position bed, were tested for their ability to maintain elevated binocular gaze, the lateral limits of their binocular vision, and their muscle balance. While gazing upward 15 degrees to 30 degrees, all the subjects experienced discomfort. At 20 degrees or more, the discomfort was serious; when elevating his line of sight this much, a man probably could not perform intricate tasks, such as piloting aircraft, with precision. It was felt that pilots should not be subjected to tasks involving use of elevated gaze beyond 20 degrees for periods of more than one hour.[9-25] Another study[9-24] concludes further that, from the prone position in fighter aircraft, the visual field is sufficient for non-combat flying, but deficient to the rear and forward in searching for enemy aircraft. Fatigue in upward gaze is insignificant when the subject looks downward at the instruments periodically. If a satisfactory substitute were devised for direct rearward vision, vision from the prone position would be satisfactory for short periods (one hour or moderately more).

Substitutes for Aircraft Windshields

Several different devices have been proposed as substitutes for aircraft windshields. These are radar, infrared, closed television circuits, mirrors, and periscopes.

Radar and infrared receivers can be ruled out as possible visual media for piloting aircraft because returns are received only from certain types of objects resolution is very poor compared with that of optical devices. Also, distance judgment is not accurate enough for landing operations with these media.

A closed television circuit is excellent from the standpoint of cockpit design, because the designer has considerable flexibility in locating the camera and display tube with reference to each other. Television has certain applications in aircraft, but can be practically ruled out for piloting, at least in the present state of the art, because of unreliability, complexities of presentations, thermal problems induced by high-speed and high-altitude flight, poorer resolutions and distance judgments than can be attained with periscopes, problems in obtaining sufficient resolution at night, and the impracticability of providing color for day usage.

Mirrors give a better image than periscopes, being free from aberrations and large light losses. However, dragwise, dimensionwise, and in flexibility in separating the receiving and display mirrors, this solution is hardly better than a windshield, except as a retractable device for use only in landing operations; for this application, mirrors merit some consideration. The geometry of mirror optics is simple and straightforward; it is easy to calculate the visual field that a mirror of given dimensions would provide, or the dimensions required to provide a given field.

Periscopes have the advantage of reliability, and they have better resolution than the other devices named, except mirrors. They are generally satisfactory from an aerodynamic drag standpoint, and offer satisfactory design flexibility in the placement of the objective lens in relation to the viewing lens. Periscopes are less satisfactory than mirrors for distance judgment and light transmission. In most other respects they are more satisfactory than any other of the devices named.

The Effect of Periscope Design on Visual Factors

Periscopes may be of an ocular type or of a display type. In the first, the eyes must be positioned close to the viewing lens, certain instrument displays must be brought into the periscopic field, and aircraft controls must be developed that can be identified by touch.

In the display type, the viewing lens is approximately 15 to 18 inches from the eyes; to prevent accommodative eyestrain, it should not be closer than approximately 15 inches. If the image plane is in the final lens, convergence will be for this distance; therefore the instrument should be designed so that accommodation is for this distance also. The viewing lens can be either a smoothly polished conventional lens, a Fresnel lens, or a lens with a ground glass surface.

From a purely optical standpoint, the ocular type is more satisfactory than the display type. The position of the lenses in relation to the eye permits a larger field of view, and the smaller lens elements permit better correction of aberrations, better resolution and light transmission, and less optical haze. In addition, the smaller exit pupil reduces the size of the objective that must project into the airstream; and because of the small objective size, two objectives might be used, one on each side of the fuselage, providing binocular vision and a good downward field of view -- an arrangement that would be less practical, for aerodynamic reasons, with the large objective of a display periscope. There remains a question that the exaggerated stereopsis caused by the wide separation of objectives may disturb the pilot. In the display type, there is a loss of resolution and a considerable optical haze if the viewing lens is of the ground glass or Fresnel variety. With the ground glass, light transmission is so low that a means for reducing ambient illumination in the cockpit must be provided. With the Fresnel and the conventional lens, the exit pupil is limited in size to about 5 to 7 inches. This size requires a large objective of similar dimension. If the exit pupil is 7 inches, it means that the head can move only 2-1/4 inches laterally from the center position without losing part of the visual field for one eye. This is often disturbing. Binocular viewing is difficult to arrange with the Fresnel and true lens types and impossible with ground glass. The display type can be used with altitude suit visor, whereas the short eye relief on the ocular type does not permit such usage.

The visual field that can be provided in the ocular type is some 80 degrees or more. In the display type, without minification, space limitations and the complexity of the optics limit the size of the field to about 35 degrees to 45 degrees as a practical maximum. When this is compared with the visual field requirements described earlier in this section, it is seen that neither of these approach the field size required for avoiding air collisions, although they answer the field requirements in most other respects. Minification that could be switched on in flight would increase the field size in the display type of instrument, but still is not likely to be practical beyond about 80 degrees to 90 degrees. Automatic scanning that would be sufficiently rapid for high-speed aircraft would almost certainly be too disturbing to the pilot.

Therefore, neither the ocular nor display type of periscope can alone provide sufficient field of view for avoiding air collision or for flying the conventional type of traffic pattern. In general, in the high-performance planes likely to employ periscopes, the available field from periscopes would be as adequate for target detection as in most aircraft having windshields. That is, the field would be narrower, but so would the zone in which an aircraft of this type could attack another aircraft (Fig. 9.4). The field of the display type would be inadequate for low-level navigation utilizing ground check points, unless side windows were provided.

In aircraft of a performance requiring periscopes, air collisions may not be much of a problem, because they may operate under ground control when they are at altitudes where other aircraft are likely to be encountered. With the display type, side windows provide a field for avoiding air collision, leaving no structural blind spot at the junction of the periscope field and that provided by the window if there is a slight minification in the periscope (which can be produced by drawing the head backward slightly).

Also, in this type of periscope with side windows, the field for the traffic pattern and ground navigation is adequate. The field through the periscope is adequate for a traffic pattern that crosses the approach end of the runway and has a 270-degree turn away from the runway.

Periscopes of other types have been designed, including optical devices attached to the head. In these, the field size is unsatisfactory for piloting and there are unsatisfactory features in their usage.

How Periscopes Affect Distance Judgment

The cues to distance judgment most used in landing operations are probably as follows. During the traffic pattern, including the first part of the final approach, aerial perspective, the angular subtense of objects of known size, and, to some extent, motion parallax provide the most usable cues (see Distance Judgment, Chapter 8). During the last part of the final approach to touchdown, the angular subtense of objects, motion parallax and, probably to a lesser degree, stereopsis are the most useful cues.

Different periscope designs affect these cues in several ways. If there is optical haze or poor resolution, the apparent distance, as indicated by aerial perspective, is accentuated. If there is real magnification or minification (as distinct from "instrument minification") in the scope, a false angular subtense and motion parallax are produced. A periscope having the objective at a location different from that of the viewing lens with a given eye distance can have unit magnification only for objects at one distance.

If the periscope is designed for unit magnification at, say, a thousand feet, this difference in position of the objective and the viewing lens can cause significant false cues only if the aircraft is close to the runway. Here, it is difficult for the pilot to think of himself as flying the plane from the objective of the scope. Consequently, the apparent magnification, giving false cues of size and speed, causes the aircraft to appear closer to the runway than is actually the case.

The reduction in the periscopic field requires motion parallax judgments to be made between much smaller angles.

In general, however, a pilot can do remarkably well under limited viewing conditions, as the following example demonstrates. Experimental flights under conditions 1, 2, and 3 (see below) were conducted in a Cessna T-50 aircraft in which sheet aluminum panels had been substituted for all plastic surfaces.[9-26] The task was to make an approach to landing from straight and level flight at 800 feet and at a distance of more than 1-1/2 miles from the end of the landing runway. The criterion of pilot performance was the accuracy of landing touchdowns in relation to a designated landing spot. The spot was defined by white target panels placed on each side of the runway approximately one quarter of the way along the landing strip. The six subjects were flight instructors. Each subject was tested five times (five landings) under each of conditions 1, 2, and 3. A different sequence of conditions was presented to each of the subjects. A second (safety) pilot did all of the flying except the landings. Conditions were:

1. Outside visual field was restricted to a square described by horizontal and vertical angles of about 10 degrees each; binocular visual cues were eliminated by the use of a projection periscope image cast on a 6 × 6-inch ground glass screen.

2. Visual field restricted as in (1), by the use of vision-reducing goggles and a vision-directing screen, but binocular visual cues not eliminated. The goggles had an opaque screen in the vision-reducer with an opening one-eighth inch square one inch in front of each eye. The screen in the masked windshield had a rectangular opening 4.2 inches high by 6.2 inches wide.

3. Unrestricted binocular vision in a normal visual flight situation.

Successful landings were made with periscope (condition 1) and goggles (condition 2). The safety of the landings was judged acceptable by the second pilot. The most accurate landings were made with unrestricted visibility (condition 3), while the least accurate landings were made with the periscope. Average error for visual landings was 85.1 feet from the landing spot; for goggle landings, it was 142.4 feet; and for periscope landings, it was 251.8 feet. The difference between the average accuracy of landings made with periscope and those made in ordinary visual flight was statistically significant, as was the difference between periscope and goggle landings.

The problem of "instrument minification" needs to be considered. Several possible explanations for this effect have been advanced. Some of them have already been proved incorrect[9-27] One of the most logical explanations is that it is due to curvature of the field. More research is needed on this problem. Some have suggested that "instrument minification" should be compensated for by a real magnification of about 1.2:1.0. The presence of a real magnification in a periscope for piloting has some obvious disadvantages, as pointed out previously. For this reason, it appears that the better solution would be to try to eliminate instrument minification in the design of a periscope as much as possible.

For night landings, a high light transmission is very desirable. High intensity landing lights have to be provided if the transmission is low, and may be necessary with the maximum transmission obtainable.

The sun is disturbing if it appears in the field of view. These effects can be neutralized by the temporary interposition of a filter.

Precipitation on the objective is less degrading to the view than is precipitation on a windshield. The reason for this is that, in the case of periscope, any point in the image is formed from light rays traversing the surface of the objective at a number of points. Therefore, a droplet does not scatter a sole light ray that forms a point in the image, as occurs on a windshield.

Degrading of the optical image from vibration is not likely to occur in jets, unless there are loose optical elements. Any degrading of the image that may occur from vibration can be remedied by damping the vibration in the periscope mounting and components.

Interference with good imagery occurs under certain conditions with severe buffeting and rough landings. This occurs if the buffeting or landing is so severe that the pilot's eyes get outside the exit pupil. Since the exit pupil on the display type of periscope is many times the size of that on the ocular type, this interference with vision is more likely to occur with the ocular type. Also, with the ocular type, unless the forehead is well supported, injury may occur with severe buffeting or in rough landings.

Orientation with Scanning Types of Instruments

Scanning types of periscopes have been unsatisfactory for piloting aircraft and may continue to be, because orientation is difficult, at least at first -- though orientation is less difficult if the dead-ahead position remains in the field at all times. Also there is no good method for determining the operation of the scan.

The periscope must not impinge on the escape space for ejection seats. This is not a particular problem with downward ejection seats. With upward ejection, no part of the scope should be closer to the eyes than about 16 inches (with the present ejection seat design).

Training

Training is an extremely important element in piloting aircraft with periscopes. The handicaps resulting from the restriction to the visual field are quite obvious and occur to every pilot before he

flies by periscope. Usually, however, he is not aware of how much he has to relearn cues for distance judgment for that particular instrument. The learning is accomplished by thorough explanation prior to flight, and, if possible, by observing landings through the instrument prior to his taking the controls. The pilot should not expect to be able to get into the plane and accomplish excellent landings after little or no instruction or experience in the use of the periscope.

VISUAL PROBLEMS CAUSED BY HIGH ALTITUDE HELMETS

There are four visual problems encountered in the design and use of high altitude suit visors. These are (1) restrictions to the field of view, (2) optical distortions produced by the shape of the visor, (3) loss of visual field through optical sights caused by the eye's being too far from the sights because of the visor, and (4) visual impairments due to fogging of the visor and to the methods used to eliminate the fogging.

Some of the transmission and distortion problems found in windshields are also found in visors; for windshields, see earlier part of this chapter.

Three typical visors that have been used by the Air Force are: One, a cone-shaped visor as employed on the MB-5 helmet; this has short radii of curvature. Two, a cylindrical visor used on the MA-1 helmet; the radius of curvature of this visor is relatively long. Three, a V-shaped visor which has been used experimentally on the MB-5 helmet.

The visual field is restricted by the size of the visor and by the limitations to head mobility caused by the helmet. A comparison of the restricted peripheral visual field with the unrestricted peripheral visual field is given in Figure 9.5. The sideward field of vision that is obtained by rotation

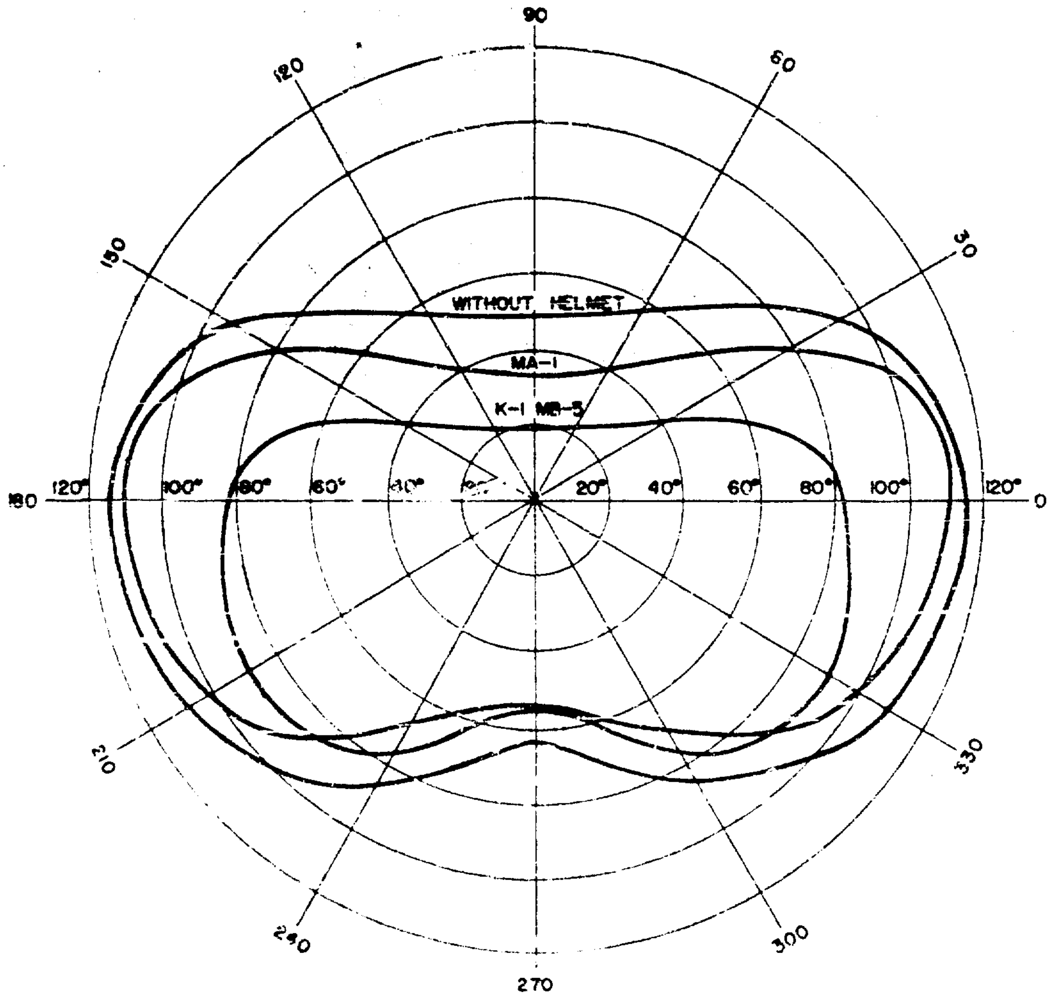


Figure 9.5 Comparison of Unrestricted Visual Field With the Field in Two Types of Helmets

of the head is additionally restricted approximately 10 degrees. The field of vision is restricted to the greatest extent by the V-shaped visor. The next smallest visual field is obtained with the cone-shaped visor. The largest visual field with the least restriction is obtained with the large-radius, cylindrical visor. Restriction of the rearward visual fields is most noticeable to the fighter pilot who requires full rearward view to detect enemy attack. A full field of view is important to crew members of many types of aircraft in order to view the consoles which are placed in nearly every available location.

The severity of optical distortions depends primarily upon the radius of curvature employed. The cone-shaped visor has the greatest distortions, due mainly to the shorter radius of curvature. The cylindrical-shaped visor has less severe distortions, while the V-shaped visor has the best optical quality of the three. However, the V-type produces very undesirable reflections, which are seldom present with the curved visors.

The visors introduce an eye relief problem when ocular-type optical sights must be utilized. The eye relief distance of an optical sight is the distance from the ocular lens of the sight at which the eye must be placed in order to obtain a full field of view. If the eye is either closer to or further from the sight ocular lens than the eye relief distance, the full field of view is not obtained. This distance varies according to the design of the optical sight. To be used with the altitude helmets presently in use, the optical sights should have a minimum eye relief distance of approximately 50 mm. This provides a full field of view through the sight for 95 percent of the suit wearers, if the suit is uninflated. Binocular sights are difficult to develop that will function satisfactorily with altitude suit visors.

Either fogging or frosting of the visor produces unsatisfactory visibility for the wearer. In addition, the provisions to prevent fog and frost formation ordinarily affect the optical characteristics of the visor adversely. The methods used to avoid these conditions are heating, air insulation between outer and inner visor elements, the drying action of an unheated or heated oxygen sweep, and a combination of these methods. All of these methods are detrimental to vision to some extent. Thus, it is necessary to consider these visibility decrements in conjunction with antifogging and antifrosting performance under various conditions.

Heating the visor may be accomplished by using an embedded wire grid or a conductive coating. The wire grid creates an annoying "picket fence" effect, as well as a slight reduction in resolution. The low light transmittance provided by the conductive coatings, with the resultant decrease in night visibility, has in the past led to a preference for the wire grid heating method over the conductive coating method. Aside from the lower light transmittance, the conductive coatings are superior in optical quality to the wire grid heating elements. Neither electrical heating method can function during escape, when the wearer is separated from his power supply.

The dry oxygen sweep method by itself has never functioned under severe conditions even when the oxygen was thoroughly heated. However, by combining the double-walled and the oxygen sweep methods, satisfactory antifogging and antifrosting conditions have been produced that function even during escape.

Fields of View

Altitude helmets restrict the wearer's field of view in several ways. The field of view is restricted by the size and shape of the visor openings. The present helmet, which is equipped with the cone-shaped visor, particularly restricts the upper and sideward areas. The oxygen valves, when mounted on the visors, restrict the downward field to an appreciable extent. More recent modifications which have placed the valves low on the visor have improved the visual field in this area.

Head mobility is reduced by the neck seals and tie-down cables, thus limiting the total field that normally is available with head and eye movements. Not only is the head restricted in its movement, but also the helmet lags behind head movements, especially when the head is rotated to its greatest extent, as when the wearer is attempting to look to the rear. In addition to these limitations, the helmet may contact various objects in the aircraft and thus prevent the wearer from placing his eyes in the position of best view. This occurs when a fighter pilot attempts rearward vision; the helmet strikes the canopy, thus preventing him from moving his head to the side sufficiently to see past the seat ejection rails and seat back in some fighter aircraft. Also, helmet contact with gun-scanning blisters prevents the gunners from obtaining the full mobility usually necessary for the maximum field of fire.

A full field of view with minimum rearward restrictions is a necessity in fighter aircraft that may be attacked from the rear and do not have adequate attack warning devices. Some altitude helmets provide inadequate fields of view for traffic pattern flying, and would expose the pilot to enemy fighters under combat conditions. The fighter pilot also has difficulty viewing the consoles placed beside the seat, while wearing the altitude suit and helmet. The bomber pilot has the same difficulty with viewing consoles mounted above, to the side, and to the rearward. With some helmets, the wearer must bend the head forward, because of oxygen valve restrictions, in order to see the lower forward instrument panel.

A comparison of the altitude helmets indicates that the large cylindrical visor provides a much better visual field, particularly in the upward and sideward areas, than does the smaller cone-shaped visor. Figure 9.8 illustrates the visual fields of these helmets and compares them with the unrestricted visual field. The fields were measured with the head in one fixed position, but with the eyes rotated maximally toward the test target. The test target was large enough so that its size did not influence the size of the visual field obtained; thus the peripheral fields rather than central fields were measured.

Tests and evaluations of the fields available to the wearer of various helmets have been found to be more accurate when the tests are made with the head held in one position. The total field -- the field available by eye and head movements and those body movements permitted by the parachute, safety harness, etc. -- determines operational suitability. However, it has been found that the total field depends upon the amount of effort exerted by the wearer in overcoming the resistance to mobility, and thus it is difficult to make accurate measurements which are repeatable. For purposes of comparison of various helmets the fixed head position method of testing has proven more satisfactory. Tests, however, have been made of the amount of mobility restriction due to the altitude helmets. With the helmet uninflated, head rotational movements are restricted approximately 10 degrees.

Optical Distortions

The optical requirements for high visual performance have long been established for corrective eye wear and for non-corrective glare-protective devices, such as sunglasses. These requirements cannot be adopted for altitude helmet visors without modification. Certain reductions in the above standards are necessitated by the size and inherent curvature of the visors and by the poorer quality obtainable with formed plastics as compared with ground optical glass.

The visors are formed from flat sheets into either cylindrical or cone-shaped visual areas. Although the surfaces are parallel, a refractive component is created by the curvature and thickness of these visors. A minus cylinder with axis at 90 degrees is created and this can amount to cylindrical lens power of -0.12 diopter. This refractive component is responsible for a small loss in the visual acuity of the wearer. It can also produce eyestrain when worn over a period of time. This refractive component of the visor can reduce the distance for detection and recognition of other aircraft as well as the resolution of objects as seen through optical instruments, such as bomb, gun and navigational sights.

The prismatic power induced by the visor is important when marked changes in prism power occur in adjacent areas, thus producing distortion. Prismatic power differences in areas viewed by each eye are particularly important where a vertical prismatic imbalance exists. A small amount of vertical prism imbalance between the two eyes can produce severe eyestrain, and even double vision, whereas the same amount of horizontal prismatic imbalance can be easily tolerated.

The shape of the visor influences its optical quality considerably. Curved visors of large radii are easier to fabricate, and can be more accurately made than visors of small radii, when a forming process is used. In addition, the inherent optical distortions are greater when small radii are employed. Both the refractive and space distortion effects decrease in severity when a long radius of curvature is present. The flat surfaced V-shaped visor is ideal from this standpoint. The greatest visual objection to the V-shaped visor is excessive reflections, which distract and interfere with visual performance. Surprisingly, the vertical line in the center, dividing the two sides, offers very little visual interference. Due to the refractive index of the material this cemented joint appears as a thin line to the wearer of the visor. Except for the reflections, the V-shaped visor provides the least amount of visual interference and the best optical characteristics obtainable in any visor design utilized. One additional disadvantage of the V-shaped visor is an undesirable limitation to the visual field. Because of these problems, the V-shaped visor is considered only for use by crew members

who are required to use optical sights. The improved eye relief distance afforded by this visor, plus the high optical quality, makes this design highly desirable for navigators, bombardiers, and gunners.

When using defogging wires, the combination of shape of visor and the wiring introduces additional optical effects. The wired section may be flat or have a spherical, cylindrical, conical, or compound curve. The spherical and compound curves are very undesirable when a wired heating element is incorporated in the visor. The difficulty in fabricating optical quality items with compound curvature is considerable by itself, and the wires induce additional distortions. With the development of other methods of antifogging, it may well be that the spherical and compound curves will provide desirable features for visor designs. With the wired visors, the flat, cylindrical, and cone-shaped configurations have provided the best optical qualities.

One approach to the optical power and distortion produced by curved visors is to design a supplementary lens system to correct those defects. These lenses are worn in goggles designed to exclude the breath from reaching the visor. Thus it serves two purposes, the correction of optical components so as to improve the visual performance of the wearer, and to provide a system to prevent the formation of fog or frost on the visor.

Eye Relief

Altitude helmets introduce an eye relief problem when the wearer attempts to use ocular types of optical sights. With these sights, the observer must place his eye at a definite distance from the sight eyepiece lens in order to use the maximum field of view available with the sight. This eye distance is referred to as the eye relief distance. Technically, it is the distance from the eyepiece lens to the exit pupil of the optical system. To obtain a maximum field of view, the pupil of the eye must be placed at the exit pupil of the optical system. If the eye is placed nearer or farther away from the eyepiece lens than the eye relief distance, the field of view available to the observer is reduced.

Table 9.3 lists the eye relief values of one type of altitude helmet. Two sets of values are listed in this table. The first set shows eye relief distances as measured to the outer vision surface. These values can be used if the sight eyepiece diameter is small enough so that the eyepiece contacts the visor only, and does not [illegible] far enough to contact the helmet also. When the helmet contacts the sight eyepiece, the visor is held out from the eyepiece and thus increases the effective eye relief distance. In this case, the second set of values listed in Table 9.3 are applicable.

Table 9.3 Helmet Design and Eye Relief Values

	Eye Relief Values for K-1 MB-5 Helmets			
	Monocular Sights		Binocular Sights	
	Mean Values	95 percent no greater than	Mean Values	95 percent no greater than
Cone-Shaped Visor				
Visor only contacts sight	35	42	47	56
Helmet also contacts sight	39	46	50	59
V-Shaped Visor				
Visor only contacts sight	30	37	Not Applicable	
Helmet also contacts sight	37	44		

Note: Helmet contacts the sight eyepiece when the eyepiece diameter exceeds 80 mm for the average user. However, to include 95 percent of the users, the eyepiece diameter must not exceed 48 mm to prevent helmet-eyepiece contact.

In order to evaluate the chances of the helmet contacting the sight eyepiece, additional measurements were made. These consisted of measuring the distance by which the straight-ahead line of sight is below the upper helmet-visor margin. This distance represents the maximum sight eyepiece radius that can be utilized without the eyepiece contacting the helmet margin. It was found that these values ranged between 24 mm and 56 mm for 95 percent of the group measured. The mean value for

this measurement is 40.2 mm. Both the eye relief distance and the distance of the line of sight below the upper margin of the visor are needed to predict the integration capabilities of new optical sighting instruments with altitude helmets.

In considering helmet visor modifications which would improve the helmet-sight integration characteristics, several possible approaches are considered. The over-all helmet size is in itself an influencing factor on the eye relief distance which the visor establishes. Reduction in helmet size would reduce the eye relief problems where helmet contact is an important aspect, as is the case with the large size eyepiece sights.

The visor-nose clearance is the limiting element in placing the visor closer to the eyes. Modifications to the K-1 type of visor shape have been fabricated and evaluated in which the visor was recessed in the eye areas to reduce to a minimum the eye relief distance and yet maintain nose clearance. This approach proved impractical because of the very small areas which were obtainable free from distortion, and because the majority of the sights used had eyepiece diameters too large to be accommodated by the small recessed visual areas of the visor.

Another approach suggested by some optical designers is to construct the visor with thick lens inserts mounted before each eye. Essentially, these lenses shorten the optical distance between the eyes and the outer visor surface, due to the refractive index of the lenses. Unfortunately, such thick lenses must be parallel to prevent space distortion, and, because of this, the outer surface is farther from the eye than is the case with a curved visor which permits a sideward eye position with monocular sights, and thus a shorter eye relief distance than is obtainable with the thick lens type of visor. In addition, this design provides a very minimum of eyelash clearance with frequent trouble with the eyelashes sweeping the rear lens surface and depositing grease upon this surface and thus reducing the clarity of the lens. In addition, there is an unacceptable reduction in the visual field required, when the sights are not being used.

The most successful modification is the V-shaped visor, consisting of flat areas at an angle to each other so as to form a central vertical joint between the two sides. This visor provides the optimum eye relief conditions and clarity of view which is required for use with high resolution optical sights. This design has two main drawbacks. The first is the reflections which occur from the flat lens surfaces. Light can enter one side of the visor, cross over to the far side, and be reflected into the wearer's eye. Since these reflections are from flat surfaces, images are formed which are visible to the wearer. When looking straight ahead, images of objects to either side of the wearer may be seen. These reflections are very distracting and annoying to the wearer. Anti-reflective coatings fail to improve this aspect due principally to the fact that the straight-ahead line of sight is not 90 degrees to the surfaces. With the curved visors, reflections can occur; however, image formation is not produced and the wearer fails to observe this type of visual interference. It should be pointed out that these reflections are not a problem while using an optical sight, and cause interference only when the wearer is otherwise engaged.

With the V-shaped visor, the head must be turned somewhat to one side when using an optical sight. This is required to position the visor flat against the sight eyepiece and thus reduce the eye relief distance to the minimum available. It is not uncommon for the user of a monocular type of optical sight to turn his head to one side as described above even though he is not wearing a high altitude helmet. This feature of the V-shaped visor should cause little if any change in the using procedures for monocular optical sights. The V-shaped visor does not improve appreciably the eye relief distance over the conventional type when used with binocular sights.

The characteristics of optical sights which are desirable for helmet-sight integration should also be considered. This is especially true for new sight designs where it is known that the users will also be wearers of high altitude suits. The sight designer should not only provide the required eye relief as listed in Table 9.3, but should also consider how these distances may be altered by helmet and visor contact with the sight eyepiece guard or shield. In addition, some sight installations are so positioned that it is awkward or uncomfortable for at least some users to place the helmet and visor squarely into the eyepiece guard.

Sights which were designed prior to the advent of the high altitude helmet may be modified to a limited extent to improve the integration characteristics. A redesigned eyepiece is a possible method of increasing the eye relief distance and thus improving the helmet-sight integration. These sights

were designed with eye cups to fit the facial features and not to fit the visor configuration. These eye cups exclude extraneous light from the user's eye and properly position the eye at the correct eye relief distance. When the altitude helmet is worn, the conventional eye cup prevents proper eye positioning and fails to exclude the extraneous light. A redesigned visor guard which covers the entire visor so as to exclude extraneous light is required. In addition, the guard must permit the visor to be placed as near as possible to the lens surface of the eyepiece in order for proper eye positioning. Some sight eyepieces have a thick lens mounting ring which in itself prevents the visor from being placed close enough to the lens for proper eye positioning. A properly constructed lens mounting ring can be substituted to overcome this difficulty.

Binocular sights are impractical when an altitude helmet is worn. Helmet and visor curvatures require a greater eye relief distance for a binocular sight than for a monocular sight. With the monocular sight the head can be turned so as to reduce the eye relief distance. This is not possible if both eyes are simultaneously used. In addition, the size of the eyepieces of binocular sights are limited by the distance between the two eyes. The longer eye relief requirement and this limitation to eyepiece diameter restrict the field of view to an impractical amount when binocular sights are employed. It has been found that 60 mm of eye relief is required with a binocular sight to provide visor and helmet clearance. The interpupillary distance may be as small as 60 mm. Due to lens mounting requirements the actual lens diameter cannot exceed 53 mm if individuals with the above pupillary separation are to be considered. The maximum angle subtended by this diameter lens from the required eye position is 44 degrees. The minimum field requirements for gun and bomb sights has in the past been 70 degrees. Since a large field of view is more important to the user than the simultaneous use of both eyes, the binocular sight is not considered to be a practical type for use with altitude helmets. Figure 9.6 illustrates these limitations to fields of view and eyepiece diameter.

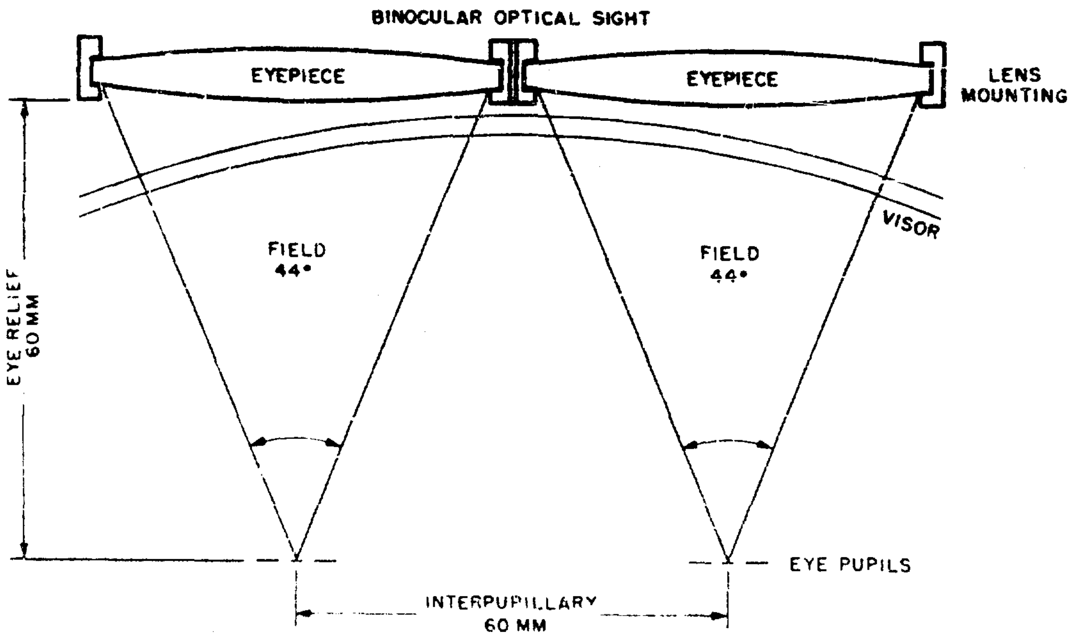


Figure 9.6 Limitations to Use of Binocular Sights While Wearing Altitude Helmets

Helmet inflation causes the visor to move forward and up. Thus the eye relief condition becomes more severe. However, the wearer can prevent this from occurring by pushing his head forward so that the visor is pressed against the sight eyepiece guard. A moderate amount of pressure is required to accomplish this. When this is done the eye relief distance which is obtainable with the helmet in the uninflated condition can be maintained and in some cases it can even be reduced. Unless the sight must be used for extended periods while the helmet is inflated, no great difficulty should be experienced.

Antifogging and Antifrosting

The inner visor surface may fog or frost thus obstructing the wearer's vision. Fogging sometimes occurs even at room temperature, and frost formation always occurs in freezing ambient conditions unless some antifogging and antifrosting method is provided. Extreme ambient temperatures are a possibility and should be provided for. These are emergency situations, such as loss of electrical power, canopy loss, or actual bailout. The power loss situation is doubly critical in that a power failure on modern aircraft usually occurs only during engine failure or some other extreme situation where the aircraft is no longer operative. With a loss of power supply to an electrically heated visor, fogging or frosting may occur at a most critical time for the wearer, who is under the stress of an emergency situation.

With canopy loss, a severe fogging and frosting condition prevails. The ambient air temperature may drop to as low as minus 65°F and the wind velocity upon the visor may be very great. Heat dissipation from the visor is thus very rapid with a resulting fog or frost formation upon the inner surface. A study of these conditions was made by the University of Michigan[9-28] The most difficult situation to provide for antifogging and antifrosting is during bailout. The electrical power from the aircraft is no longer available. In addition the worst conditions of temperature and wind velocity are likely to prevail. At times accumulated pools of perspiration may have collected in the neck area of the helmet and this is thrown upon the inner visor surface where it quickly freezes during the free fall period of bailout. The wearer's loss of orientation during such a situation may easily induce him to prematurely actuate parachute opening.

Several methods are in use or have been proposed to provide antifogging and antifrosting characteristics. The first to be discussed is the wire grid. This grid is laminated between plastic layers. Diffraction produced along each wire is responsible for a slight reduction in the resolving power of the eye. Wearers sometimes observe a picket fence effect, i.e., alternate dark and light streaks in the visual field. The dark streaks, even though they never obscure even the smallest target, appear to be wide and all out of proportion to their actual width, compared with the space between the wires. This effect reduces visual performance more by distraction than by actual reduction in visual resolution or acuity. The wires have been a considerable source of trouble to the visor fabricator. They have been a source of distortion defects in the plastic layers. Improved fabrication techniques were required to permit the fabrication of visors of good optical quality.

Electrically conductive transparent coatings are another method of providing antifogging and antifrosting. The Nesa and Electrapane coatings have been used for this same purpose on aircraft glass windshields. However, the development of similar coatings for plastic materials has lagged behind that for glass. Problems of adherence, sufficient light transmittance, and sufficiently low resistivity have plagued the developers of these coatings. The use of a coating eliminates many of the disadvantages of wires, and permits the fabrication of higher optical quality plastic visors. It appears best that these coatings be laminated between layers of plastic to prevent scratching and the resultant development of hot spots and the eventual disintegration of the conductive coating. The use of either an overcoating or a very thin laminate layer so that the conductive coating may be placed very near the inner visor surface greatly reduces the heating requirements for the element.

It is highly desirable that the visor have a light transmittance value in excess of 80 percent, and that the conductive coating resistivity be less than 20 ohms per square area. The attainment of these two requirements has as yet never been simultaneously demonstrated. The objectionable features of the coatings are the increased reflections which are annoying to the wearer and the loss in light transmittance which adversely affects night visual performance.

Another method to prevent fog and frost formation is to use the incoming dry oxygen to dry the visor by causing it to sweep across the inner visor surface. Commonly this is done by directing the

oxygen from the helmet inlet valve through a tube which passes around and across the top of the visor opening. A series of small holes are properly spaced and located so that the oxygen is directed from along the top, downward across the visual area. This method by itself has never been proven to be effective under cold conditions. When used by itself the best that can be expected is that a small area near the outlet holes may be maintained free of fog or frost.

The U. S. Air Force altitude helmets permit the exhaled air to contact the visor thus providing excellent conditions for fog and frost formation. The U. S. Navy altitude helmets contain a face mask which directs the exhaled air out of the helmet and prevents this air from contacting the visor. An oxygen sweep method is used to keep perspiration and moisture, which may leak from the face mask, from fogging or frosting the visor. This method has the advantage of eliminating the necessity for electrical power and thus is attractive for emergency situations. The Navy method also has several disadvantages. One complaint frequently made by wearers of this type of helmet is that the additional discomfort of the face mask imposed upon that of the helmet is undesirable. Considerable difficulty has been experienced in keeping the mask in place during head rotational movements, where the helmet lags behind head movements and drags the mask with it. Under these conditions, mask leakage is very evident and visor fogging or frosting results. The comment has been made by some wearers that if you are not active it functions.

Another method or combination of methods shows promise. The oxygen sweep when combined with a double-walled or thermopane type of visor has been tested to very low temperatures without fogging or frosting of the visor. This method depends upon a dead air space between the walls of the visor to provide insulation, and on the oxygen sweep across the innermost surface to assist in preventing moisture deposition. This type will be used on a series of very high altitude parachute jump tests, where electrical heating is not practical. The disadvantages to this design are the increased reflections provided by the multiple visor surfaces, and the problems of distortion magnification which occur with multiple transparent elements. In addition, the lack of accessibility to the between layer surfaces for cleaning is another problem.

Various chemical antifogging preparations, either in a solid or liquid form, separately or on an impregnated cloth,are available for several common uses such as prevention of fog formation on eye glasses, windshields, goggles, mirrors, etc. These chemicals are all wetting agents and are hydrophilic in action. A perfectly clean surface, if possible to obtain, would function in the same manner. Essentially these agents prevent droplet formation and induce the sheeting out of the water layer, thus maintaining a good optical surface. The deposition of water upon the surface exists with the use of wetting agents and therefore freezing is not prevented. Under perfect conditions the ice layer is clear with good optical characteristics. However, the least surface imperfection can be the origin of a frosted condition which rapidly spreads over the entire area, destroying the optical quality of the ice layer. Thus antifog chemical preparations are of little use under freezing conditions.

OPTICAL TELESCOPES (BINOCULAR AND MONOCULAR) FOR PILOT USAGE

Binoculars for pilot usage can be of great value in identification if they are properly designed for the purpose. The critical difference between the use of binoculars by pilots and other individuals is one of time. The pilot must be able to promptly shift his view, back and forth, from direct vision to the view of the object in the binoculars. The best solution to this problem appears to be a helmet mounted binocular with an angulated sight line.

Need

Binoculars are needed by pilots in certain phases of missions, in order to extend the range of vision. The advantage of extending the visual range is to identify an object as enemy before the enemy can detect and identify. This gives a tremendous advantage in positioning for attack, avoiding vulnerable approach, or in evading attack.

It is useful to extend the visual range for search and for identification. Search is the scanning performed in order to detect objects of possible interest. Identification is the determination of the nature of a detected object, sufficiently exact for the purpose at hand. Therefore, search is the first phase of the search and identification procedure, and involves scanning. Identification is the second phase, and does not involve scanning, except for the location of the detected object in the field of view for identification purposes.

The performance of binoculars in search is different from their performance in identification, because of the scanning necessary in search. For binoculars to be of value in search, objects must be detected at a greater range than with direct vision. Even though the range at which objects can be seen with binoculars is greater than with direct vision, search for the objects presents a problem because the field of view through the binocular is much smaller than the field of view with direct vision. Therefore, several times the number of fixations have to be made with the binoculars. In order to detect objects at a greater range with binoculars, search of the necessary area must be completed in less than the time required for the aircraft to travel the difference between the binocular range and the visual range, plus the time required to complete the direct visual search. For example, assume that the binocular range is six miles, the visual range is three miles, and the aircraft would travel one mile in the time required to complete a visual search. For the telescope search to be of more value than the visual search (based on 100 percent probability of detection), it must be accomplished in less time than is required for the aircraft to travel 6 - 3 + 1 = 4 miles. Since a large number of fixations are required to completely search a field through binoculars, the faster aircraft travel a considerable distance during this time, consuming most of the difference in visual range.

In a comparative trial of binocular and visual search[9-32], the smallest available marine target (a radar training buoy) was used. The binoculars of 8x magnification normally issued to reconnaissance or sea-search crews were used. Aircraft crews and two observers made 101 runs in bomber and reconnaissance aircraft. Only one of the two observers used binoculars, although both were given the same sector to search and both had identical lookout positions (bombardier or co-pilot's position). Naked-eye search missed the target on fewer occasions than search with binoculars, but when the buoy was sighted by both lookouts, the average range of sighting was greater with binoculars. Other sources[9-37,9-52,9-53] indicate that, in the present stage of the art of detecting objects from aircraft by day, naked-eye search is generally more effective than search with binoculars. They usually do not increase sighting range appreciably when visibility is less than five miles. Also, since the use of binoculars lowers pilot performance in other respects, binoculars are of value in search only when a very small field has to be searched.

On the other hand, the value of binoculars is definite in identification, where the object has been found already by naked-eye search. Identification should always be faster through the binoculars, except where there is excessive time loss in finding the previously detected object in the binocular field. If there is a means of promptly locating the detected object in the binocular field, there is no appreciable field to scan, and so ordinarily a large amount of time is gained in identification through the binoculars. Therefore identification by binoculars has a definite range advantage over that by direct vision, provided some of the problems in binocular usage are solved.

There are several important operational needs for extending visual range. In tactical air warfare, there is the need to identify air objects without approaching any closer than necessary. The first identification of an opposing aircraft gives a tremendous and often decisive advantage over the enemy, in positioning for attack, or in evading attack. There is also the need to identify ground objects at the maximum range. This is necessary in order to avoid reconnaissance flights over heavily defended points, and to avoid flights over certain points that would disclose that reconnaissance has been made.

In the strategic mission, extension of visual range is needed to ensure the earliest identification of other aircraft by bombers and by their escort fighters.

In the air defense mission, there is a need for the earliest identification of aircraft, without getting within vulnerable range.

In the air rescue mission, the effectiveness of the search for survivors can be increased by extending the range for search and for identification. Extension of the identification range enables a pilot to identify suspicious objects off his prescribed course without making unnecessary deviations. In this type of mission, in multiplace aircraft, the effectiveness of a search phase may also be increased by the other crew members using binoculars. Binocular search in this case is more likely to be of value, in comparison with direct visual search, because each crew man can be responsible for only a small search area.

Types of Binoculars

Several problems must be solved in order for binoculars to be of value to a pilot. He should be able to use them in a large field about the aircraft, in some cases up to 330 degrees in azimuth. He must be able to change his view promptly from aided vision (i.e., through the binoculars) to unaided, and back to aided. That is, upon detection of an object by direct vision, he must be able to locate it promptly in the binoculars; and he must be able to scan promptly the aircraft instruments and scan outside the aircraft, in order to avoid collision.

The binoculars must not be subject to vibration or hand tremor. They must not be so bulky as to strike the canopy unnecessarily when the pilot is looking over the side of the aircraft. The weight must be acceptably low for static support and so that they will not push too hard against the head or be wrenched away under high g-forces. The binoculars must not interfere with other equipment and procedures.

In general, binoculars can be designed to be used in three ways -- plane-mounted (i.e., mounted on the aircraft), hand-held, or helmet-mounted.

The plane-mounted binoculars solve the weight and hand tremor problems, but they are not very useful, because they cannot be designed to sweep the required field freely. This design has little possibility for success in future development.

The hand-held binoculars solve the vibration problem fairly well, but hand tremor is still a factor, especially when the aircraft is subjected to buffeting. The effects of tremor can be corrected only by stabilized optical elements, which add to the weight of the instrument. The pilot cannot shift his view promptly back and forth from the binoculars to the aircraft instruments and the outside and back to the binoculars. No satisfactory means has as yet been devised for finding an object promptly in this type of binoculars. In hand-held monocular telescopes, ring sights attached to the monoculars facilitate finding objects; otherwise they have the same deficiencies as hand-held binoculars. The weight is unacceptable for protracted usage or when the pilot is subject to high g-forces.

Helmet-mounted binoculars are satisfactory for prompt shifting of view and for finding an object in the telescopic field if the optics are angled so the pilot can see five degrees or more above the horizon with his naked eye, under the binoculars.

Binocular Optical Systems

Two main types of binocular optical systems are in general use today. The Galilean is by far the simplest type from a design viewpoint. This design is utilized in the so-called "Sportscope," or spectacle binoculars, as well as in opera glasses. The instruments are small, compact and lightweight.[9-40]

The Galilean system employs a positive objective lens and a negative ocular or eyepiece lens. An erect image can thus be achieved without resorting to the multiple reflections of the image that are necessary in a prism binocular. However, the exit pupil of the Galilean system falls between the objective lens and the ocular. The system thus suffers from a narrow field of view even when the eye is placed almost in contact with the ocular. When the instrument is required to have 20-30 mm eye relief, as in helmet-mounted binoculars, the problem of achieving a sufficient visual field is accentuated.

The chief advantage of the Galilean telescope is its short over-all length, which suits it for use as an opera glass. Also, since there are only four air-glass surfaces, the images are very brilliant and free from flare. On the other hand, the small field of view is a serious disadvantage, and consequently the highest practical magnifying power is about 2x[9-49,9-50]

The need for a compact erecting telescope of magnification higher than 2x is met by the prism binocular. It is essentially an astronomical telescope (positive objective lens and positive ocular) with prisms inserted in the light path. The prisms serve to diminish the length of the instrument and to invert and reverse the final image so that it is presented to the eye in correct orientation. Various types of prisms are used; the so-called "Porro system" is the most common. It consists of two right-angle prisms, the first of which inverts the image; the second reverses it right to left[9-49,9-50,9-51]

The prism binocular is considered to be more suitable than the Galilean for a helmet-mounted binocular, since the prism binocular has a suitable magnification (at least 3x is desirable) and its eye relief is better and its field size larger than in the Galilean.

Design Characteristics that Affect Visual Performance

The human eye itself must be considered in the design of binoculars[9-38,9-45] The detection range of the eye depends upon five variables: (1) the inherent target area, (2) the inherent target contrast, (3) the brightness of the background against which the target is viewed[9-43], (4) the meteorological range, and (5) the shape of the target. Visibility charts are available which make it possible to compute the detection range of the unaided eye[9-38] Binoculars affect these variables by magnification, contrast rendition, light transmission, and exit pupil of the binocular[9-45]

A myriad of studies on magnification are reported in the literature[9-31,9-33,9-34,9-50] In summary, it should be remembered that visibility is not improved in direct proportion to the amount of magnification. Whenever allowances are made for atmospheric conditions[9-48], effects of vibration, etc., it is seen that the increase in range at which a target is just detectable with the naked eye is not proportionately increased with the magnifying power of binoculars[9-30,9-41,9-44,9-46,9-47] This is especially true in hazy or smoky atmosphere. A series of curves has been prepared [9-45] which show this.

As pointed out above, magnification is a hindrance in using binoculars for most search purposes. For identification, magnification probably should not exceed 4x in helmet-mounted binoculars due to alignment and vibration factors. If the optics can be stabilized in a hand-held instrument, an increase in magnification would be in order[9-29,9-57]

The apparent brightness of a binocular image depends on the light transmission of the optics[9-33, 9-38,9-59] In general, the brighter the image the easier it will be to see. Therefore, it is important to keep the number of air-glass surfaces to a minimum and to coat all these surfaces with anti-reflection coatings. A gain of approximately 25 percent in light transmission is possible by using a magnesium fluoride coating. In terms of increase in range, this means very little in bright daylight. At night, an increase in range of approximately 15 percent can be effected[9-30,9-54,9-58]

The light-gathering power of binoculars depends upon the diameter of the objective lenses[9-51] Large diameters are important only at night when there is little light available and the pupil of the eye is large.

The exit pupil size is one of the most important characteristics of binoculars[9-30,9-49,9-57] The exit pupil is the image of the objective formed by the ocular. The brightness of the retinal image in the eye is at a maximum when the pupil of the eye is filled with light, and it decreases in proportion to the area of the exit pupil when the exit pupil is smaller than the eye pupil. Ideally, therefore, the exit pupil should be the same size as the entrance pupil of the eye.[9-49] However, in practice, the exit pupil size is generally larger to compensate for any misalignment with the eye.

The pupil of the eye varies from a diameter of approximately 2 mm in daylight to 8 mm in darkness. Therefore, the required exit pupil size depends upon usage. In binoculars to be used only in daylight, the exit pupil probably need not exceed 4 mm. For use at night, the size should be increased[9-35,9-54]

Eye relief is defined as the distance from the last surface of an optical instrument to the plane of the exit pupil of the system[9-49,9-50,9-57] If the eye relief is short, the eye must be placed very close to the ocular lenses, in order to utilize the full field of view of the binocular. In an airplane, where vibration is a problem and turbulent air may cause a bumpy ride, it is important that the ocular lenses be far enough from the eyes to keep the binoculars from striking the head. Therefore, the eye relief should be longer in this type of binoculars than would usually be necessary in conventional types. In addition to the safety factor, binoculars with short eye relief are difficult to use, since they must be pressed constantly against the head in order to obtain a full field of view. On the other hand, binoculars with too great an eye relief will be more difficult to align.

It is easy to specify the optical qualities of an instrument. These are expressed in terms of light transmission, resolution, aberrations, and lens defects[9-42] However, supporting these

specifications with experimental facts to show how performance varies as a function of optical quality is very difficult. It appears that the specifications have been set up in order to obtain the best possible instruments in all respects. For military purposes this may not always be necessary. For instance, if the main use of binoculars is for identification and the instrument can be positioned properly, the resolution might be degraded considerably near the edge of the field with no adverse effect. The same rationale can be applied to other specifications for binocular elements. Unfortunately, some of the basic data dealing with detection and recognition thresholds are not yet available, although work is progressing in these areas[9-39] It is the feeling of some that until this sort of information is available, specifications for quality in binoculars cannot be based on the needs that they are intended to satisfy.

Aircraft using reciprocating engines have a certain amount of vibration imparted to the air frame by the engines. This vibration will have an adverse effect in using binoculars. For instance, consider an observer using binoculars for aerial reconnaissance. If he steadies his arms by resting them on any part of the aircraft, some of the vibration of the frame is transmitted to the binoculars. If the air frame is not touched, the problem is not so great, since the user's body absorbs some of the vibration. However, hand tremor will increase after a short period, since there is no way to steady the arms. Thus the effect slowly returns. There are special methods which will reduce the vibration problem for practical purposes. The use of stabilized optical elements in hand-held binoculars has already been discussed. Helmet-mounted binoculars take advantage of the natural absorption of vibration by the body and are not subject to the hand tremor of conventional models. Thus, in the helmet-mounted binoculars, vibration is reduced to an unimportant amount.

The angular field size of binoculars useful in military aviation can be determined in large part by the purpose for which the binoculars are to be used. In the past[9-31,9-33, 9-57] there has been no rationale in determining field size except "the larger it is, the better." Actually, for identification purposes, a small angular field will be just as useful as a larger field if the problem of finding a previously sighted object in the binoculars can be resolved. In search, a larger field would be necessary.

Finding objects previously sighted with the naked eye in the binoculars' field has proved a vexing problem. No solution is seen to this problem with hand-held binoculars. In helmet-mounted binoculars, the problem is taken care of easily if an angulated sight line is used. In binoculars of this type, as soon as an object of interest is sighted, a quick glance up into the field of the binoculars will show a pointer directed at the object of interest. If the pointer is not desired in the field, the object can still be located with a minimum of effort, although it will not be exactly pinpointed. In monocular hand-held instruments, a ring sight is sometimes attached where the other half of a binocular would be. An object placed within the ring as seen with the unaided eye can be seen magnified by observing the magnified image of the other eye.

Most persons using binoculars have duties to perform other than observation through the binoculars. There is no easy way to change fixation back and forth from conventional binoculars to flight duties and back to binoculars without losing orientation. Hand-held binoculars must be taken away from the eyes to perform other duties. The head must be removed from plane-mounted binoculars in order to perform other duties. The two-position helmet-mounted binoculars must be rotated upward. However, the angulated sight-line helmet-mounted binoculars can remain in place. A simple downward shift of the eyes allows other duties to be performed. Shifting the eyes upward puts them back in the field of view of the binoculars. This is a very rapid change, dependent only on the time necessary to move the eyes, to converge or diverge, and to accommodate. When using the other two types, the change is slower and it takes some time to get reoriented when using the binoculars again.

The bulk and weight tolerable in binoculars depend upon the way they are to be used. The weight and bulk of a plane-mounted binocular can be fairly large and cause no particular difficulties[9-31, 9-33, 9-57] The bulk of hand-held binoculars is not a very important consideration. However, helmet-mounted binoculars must be as compact as possible else it is very difficult to look over the side of the aircraft. To be useful to a pilot, the binoculars should not restrict normal head movements. The bulk of helmet-mounted binoculars, therefore, has to be restricted in order to avoid striking the canopy. This can be improved by placing the objectives close together; this permits a wider range of movement with unobstructed vision between opaque canopy structures, and thus is a logical choice in design. The loss of stereopsis by moving the objectives closer together is not important at the distances binoculars are used.

Hand-held binoculars should probably weigh no more than two pounds, since they must be held up with the unsupported arm. This light weight will be less fatiguing and hence will cause less hand tremor. The weight of helmet-mounted binoculars is an important consideration since any weight added to the helmet is undesirable. Weight added to the front of the helmet is particularly undesirable since it tends to unbalance the helmet and increase the likelihood of downward rotation in the event of a large g-force. Every effort must be made in the design of helmet-mounted binoculars to keep weight to an absolute minimum. Plastic optical elements which weigh less than glass parts can be employed to good advantage in reducing the weight of the binoculars. At the present time, however, the plastic is not sufficiently abrasion resistant to be used for outside optical elements[9-33]

Monocular vs. Binocular Instruments

Available experimental evidence indicates that observation through binoculars is superior to observation through monoculars for picking up targets under adverse conditions[9-55] There is, however, no general agreement on the extent of this superiority; values ranging from 10 to 50 percent have been reported in various investigations. Nor is there any common agreement for superiority of binocular viewing. Subjectively everyone prefers binocular vision. This problem cannot be said to be solved since information on studies of this sort is incomplete.

METEOROLOGICAL CONDITIONS AND TIME OF DAY

The light from an object on the ground or another aircraft passes through a great deal of atmosphere before it reaches the pilot's or observer's eye. Except for close objects or where the intervening atmosphere is very thin, as in air-to-air visibility at high altitude, the effect of atmosphere on transmitted light must be considered when direct vision from aircraft is being evaluated.

Fortunately, research in recent years has provided us with tools and concepts to assess the optical effects of the atmosphere. The parameters of an optical signal arriving at the observer's eye can be defined, provided only the quantity and direction of illumination, the transmitting or reflecting properties of the object, and certain optical constants of the atmosphere are known. In this discussion, we will briefly describe the major effects of the atmosphere on vision in flight. The best sources of detailed information are contained in recent papers of one investigator[9-63,9-64,9-65,9-66] and in an excellent volume[9-74] from which this discussion has in large part been drawn.

The atmosphere works in two ways to change the appearance of objects seen through it. One is atmospheric attenuation. The other is the addition of light from the atmosphere, so that distant objects seem lighter. Atmospheric attenuation is the loss of light by absorption and scattering, so that it does not reach the observer's eye -- or at least does not reach the correct spot on his retina to form a coherent image. A simple example is the loss and scattering of light from a beacon at night, so that at a distance the light source appears dim, and its exact shape cannot be discerned. Addition of light from the atmosphere most commonly changes the appearance of objects during the day, and it is most important for objects that reflect light rather than transmit it. It comes about when light from another source than the viewed object, such as the sun, is reflected or refracted by the atmosphere so that it follows the same path to the eye as light from the object. Since light from the object is being lost at the same time through atmospheric attenuation, the net result is that a dark object both appears lighter and stands out less clearly from surrounding objects. This effect is most commonly seen in the appearance of distant mountain ranges, whose dark forests appear progressively lighter with increasing distance. The effect is due to the illumination of the air path; its magnitude, as will be seen, depends upon such factors as the strength of this illumination, the constitution of the atmosphere, the length of the path of sight, and the geometry of the paths of light and line of sight. The consequences of attenuation and addition of light will be described in some detail later in this section. First, however, we will describe briefly the properties of the atmosphere that are responsible for these effects. We will also describe how quantitative data may be obtained, so that the effects can be evaluated.

Optical Composition of the Atmosphere

It is convenient to think of the atmosphere as a colloidal system in which the gases that make up pure dry air support a mixture of particles and water vapor. This colloidal system varies widely at different times, places, and altitudes. It may be shown that pure, dry air is an almost perfect medium for the transmission of optical images in the visible spectrum; the visibility range in such an

ideal, nonexistent atmosphere would be more than 200 miles. It is therefore obvious that nearly all of the limitations to optical transmission imposed by the atmosphere are due to particles of matter in the air.

These particles are of nearly infinite variety. However, the most important ones seem to be water in its various forms, smokes, dusts, sea-salt nuclei, and industrial pollutants. For our purposes, most of the important optical properties of the air are due to spherical liquid droplets of various sizes[9-74] Such droplets are most numerous in fog, haze, clouds, and rain, but they are present in appreciable quantities throughout the troposphere.* Thus the lower atmosphere may be regarded as a turbid medium; by applying the optics of turbid media, one can find the magnitude of the changes that take place when an image is transmitted through the air.

Optical Structure of the Atmosphere

The density of the permanent gases of the atmosphere decreases approximately as an exponential function of altitude. While the suspended particles follow the same over-all pattern, there are many local variations; typically, these particles concentrate in patches and layers. Where they are densely concentrated, haze, clouds, and fog appear.

Since the concentration and nature of particles vary both vertically and horizontally over short distances, tracing light through the atmosphere can be a complicated process. Detailed meteorological measurements are required at many or all points along the path of light. Such measurements were recently made by a specially instrumented B-29 aircraft operated by the Visibility Laboratory of the Scripps Institution of Oceanography. They reveal that even portions of the atmosphere that appear clear and homogeneous may have a very complex structure indeed. Further techniques are being sought for studying light transmission through atmospheres of varying optical properties.

Image Degradation by the Atmosphere

Since the atmosphere is not a perfect transmission medium, signals arriving at the eye from a distant stimulus are some degraded function of the inherent properties of the stimulus.** The important properties of the stimulus are its brightness, contrast, and color. The apparent brightness of an object seen at any distance is a function of its inherent luminance, the properties of the transmitting medium (absorption and scattering), and the geometry of the path of light. The apparent contrast between objects, or between an object and its background, is related in the same way to the inherent brightness of the objects or the object and its background. (However, we shall see that the sky background is a somewhat special case.) The relation of apparent color to inherent color*** is more complicated and less well understood. One worker[9-74] has made an admirable analysis of color changes from both the physical and psychophysical points of view, the psychophysical part being based upon the work of another researcher[9-73] However, the principles he worked out are not always easy to apply, because the perception and discrimination of color are complicated by many psychological variables. (Color specification is explained in Chapter 2 and color discrimination in Chapter 8.) For example, to predict the apparent color of self-luminous signals at low ambient illumination, it is not enough to know what portions of the spectrum the atmosphere will transmit. In this case, a more important factor is the peculiar performance of the eye when observing colored signals that subtend a small visual angle[9-69]

---

* The troposphere is the portion of the atmosphere nearest the earth, below the stratosphere. Its upper limits vary with time and place from about 20,000 feet to 50,000.

** The inherent properties are those that are due to the nature of the stimulus itself rather than the transmitting medium. They can best be defined as the properties that would arouse a given response if the stimulus were observed through a perfect transmitting medium.

***Brightness, of course, is usually considered one attribute of color (see Chapter 2). When we speak of color here as a property distinct from brightness, we mean the attributes of color generally defined as hue and saturation.

Fortunately, brightness contrasts are both easier to analyze and far more important than color in detecting and identifying distant objects. Objects can be discriminated by their brightness contrasts at greater range than they can be discriminated by their color. A moment's thought will show how important brightness contrast is. Suppose, for example, that a pilot is searching for enemy aircraft. He will not detect another aircraft unless it contrasts sufficiently with the sky or land it is seen against. He will not identify the aircraft unless it constrasts sufficiently with its background and unless its components contrast sufficiently with each other so that he can make out its shape and markings. He will not be able to judge its speed and course unless the contrast is sufficient so that he can continually see the aircraft as it changes position relative to its background. (In this case, a change in background brightness as the aircraft passes in front of clouds or over a mottled landscape may be important.) The pilot's ability to do these things depends of course on his visual acuity, motion perception, etc., but in this case visual acuity and motion perception depend in turn on the brightness differences of images falling on adjacent receptors in his retina.

In the following paragraphs, we will explain how contrast is reduced as light passes through the atmosphere, and the consequence of this reduction. The treatment is that suggested in a study conducted in 1948[9-63]

Contrast Reduction by the Atmosphere

The value of apparent contrast (the contrast as seen at a distance) may be determined from (1) the value of the inherent contrast (the contrast at the stimulus) and (2) values of the transmission and scattering functions of the atmosphere. Now, brightness is reduced exponentially as light passes through the atmosphere (see equations 10 and 11 in 1948 study). As would be expected, contrast follows similar exponential laws, since it is a function of brightness. The attenuation of brightness differences is:

$$\underline{B}_R - B_R = (\underline{B}_o - B_o)\, e^{-\beta_o \overline{R}} \qquad (1)$$

where;

$\underline{B}_R$ and B_R are the apparent brightnesses of the object and background, respectively, at range R, $\underline{B}_o$ and B_o are the inherent brightnesses of the object and background, β_o is the atmospheric attenuation coefficient (consisting of factors for absorption and scattering), and

$\overline{R}$ is the "optical slant range".*

Since contrast is defined in terms of brightness differences, it may be seen that:

$$\text{inherent contrast} = C_o = \frac{\underline{B}_o - B_o}{B_o}\text{, and} \qquad (2)$$

$$\text{apparent contrast} = C_R = \frac{\underline{B}_R - B_R}{B_R} \qquad (3)$$

We may now write the original equation in terms of contrast, as follows:

$$C_R = \frac{B_o}{B_R}\; C_o e^{-\beta_o \overline{R}} \qquad (4)$$

which is the general law of contrast reduction by the atmosphere.

The investigator[9-63] in this study has derived equations for an observer looking upward and downward, and for horizontal paths of sight. In the last case, the equation reduces to:

$$C_R = C_o e^{-\beta_o \overline{R}}, \qquad (5)$$

provided that the horizon sky is the background against which the object is viewed.

*The equivalent horizontal path through a homogeneous atmosphere.

In any practical application of equations (1) through (5), of course, the optical constants of the air must be determined by measurements. Unfortunately, however, such information is almost never available to the pilot, because meteorologists fail to provide it in their so-called "visibility" estimates. Where the measurements are made, however, and viewing conditions are predicted accurately enough, the foregoing formulas can be used to develop nomographs, so that sighting ranges of objects at various angles and distances can be predicted quickly by pilot or crew. The nomographic method has serious limitations at present, because the values for inherent brightness in the formulas cannot be determined when the target is moving or has a complex shape or internal contrast pattern. That is, in these cases, there are multiple contrasts, and not enough is known about how the eye operates to evaluate them. Note that these limitations are not due to lack of knowledge of atmospheric optics, but rather to the lack of knowledge about the operating characteristics of the human eye in complex visual situations. At this writing, however, several active research groups are vigorously attacking these visual problems, and predicting visibility is becoming increasingly accurate in complex situations.

Problems of Visibility During Flight

No matter how good the techniques for calculating visibility become, they will be of little practical use until meteorologists measure the characteristics of the atmosphere that affect the optics of the light passing through them. While means of measuring them are fairly well known, most meteorologists are unaware of the need for such measurements and lack the proper instruments to make them. Therefore, nearly all estimates of visibility for airmen are crude guesses, usually based on the appearance from the ground of objects that just happen to be at convenient distances from the meteorology station. It is of course true that visibility changes minute by minute and mile by mile in flight, but, the practical shortcomings of such crude estimates are covered in some detail by one researcher[9-74]

However, scattered studies of atmospheric variables, some of them field tests, have been made that do have some bearing on visibility during flight. The more important conclusions from these are described in the next paragraphs.

The range at which a given target can be seen in daylight is largely determined by its apparent area and contrast[9-71] Furthermore, the contrast of a given target depends on the altitude and relative bearing of the sun as well as upon the amount of atmospheric haze. For these reasons, detection is most effectively carried out between midmorning and midafternoon. One investigator[9-60] developed a set of charts from which the natural illumination can be computed at any time of any clear day or night in the year at any point on the earth. As one would expect, the values vary considerably with season and latitude, and factors like haze and clouds have a great effect. The horizontal attenuation of ultraviolet and visible light by the atmosphere has been measured[9-62] at night over cities, deserts, and the sea under conditions ranging from fog to exceptionally clear air. From these measurements, attenuation coefficients were derived for light of various wave lengths for some of the locations. The tables are for those who require a survey of typical spectral attenuation characteristics of the lower atmosphere. For those requiring accurate coefficients for a given time and place, this study[9-62] describes methods for making the required measurements. The data collected so far show that attenuation in the atmosphere over a city follows a less regular and more complicated pattern than over a desert or sea station. The composition of smogs is difficult to analyze.

The brightness and polarization of the daylight sky at altitudes of 18,000 to 38,000 feet above sea level have been measured by one team of researchers[9-75] Their results agreed fairly well with another team's[9-76] theory of sky brightness for all altitudes of observation, for all points in the sky more than 30 degrees from the horizon, and for scattering angles greater than about 40 degrees from the sun when an atmospheric attenuation coefficient of 0.017 km was assumed. The values of sky brightness observed at scattering angles within 30 degrees of the sun indicated that large scattering particles were present in the atmosphere overhead at all altitudes of observation. The measured values of sky brightness and polarization are presented graphically, plotted as functions of the angle between the sun and the observed point in the sky.[9-75]

One study[9-67] estimates visibility from high-speed, high-altitude aircraft. At 600 knots, an aircraft travels 10 miles in one minute, and at 1200 knots, it travels 10 miles in half a minute. Objects may therefore appear and disappear from view in sudden fashion. A pilot must therefore be able to respond to slight visual cues before it becomes clear that they are actual targets. Having

pointed out the problems, the author of the study computes visibility based on visual acuity data corrected for the effect of atmospheric attenuation at various altitudes. Visibility above 50,000 feet is approximately the same as at 50,000 feet, because the effect of atmospheric attenuation is negligible above this altitude. In the text of the study[9-67] graphs are presented to show threshold visibility in all directions at altitudes up to 200,000 feet. Other sources of information are available[9-58,9-61, 9-68,9-70,9-72] On the matter of field checks on laboratory predictions of threshold intensities of long-range targets, see Report on the Roscommon Visibility Tests[9-59]

The concept of meteorological range[9-63] is being accepted as a precise designation of atmospheric clarity in terms of distance. Meteorological range is the distance for which the contrast transmission of the air is two percent. It is an inverse function of β, the attenuation coefficient. The acceptance of this concept may lead to more useful systems for collecting data at the individual meteorological station.* Knowing meteorological range, a pilot can use the nomographs previously mentioned to predict the visibility of objects seen against the sky. However, additional problems come up in predicting the visibility of objects seen against the earth along horizontal or downward paths of sight; the worst problem is that the atmosphere is not uniform optically along such paths. An extensive program is now underway to increase our knowledge of the optical structure of various portions of the atmosphere, so that the known principles of atmospheric optics can be applied to any problem.

Conclusion

The foregoing is a summary of the current status of knowledge about how the atmosphere affects visibility; specific problems likely to be encountered in flight will be discussed in later chapters. In Chapter 10, on air-to-air visibility, specific instances are given of the influence of atmosphere on visibility.

VISUAL ILLUSIONS

Visual illusions leading to false aircraft attitude orientation are of four different types:

(1) False Reference

(2) Autokinetic

(3) Oculogyral

(4) Oculogravic

The false reference type of illusion may be present in day or night flying. In the daytime the most frequent source of false reference is cloud formations that have slanting lines that are mistaken for horizontal. Another false reference illusion occurs in formation flying when another aircraft in a bank, a climb or a descent is thought to be level.

False reference illusions occur at night when the stars near the horizon are mistaken for lights or vice versa, creating a false horizon. This is especially likely to occur if there is no haze to mark the horizon, which condition often occurs after a rain. The likelihood of this illusion is also increased if there are clouds that are seen entirely below or entirely above the true horizon.

The autokinetic illusion occurs at night. The illusion is that a single stationary light appears to be moving when the observer stares at it.

If, instead of a single light, there are several lights or some kind of figure, there does not appear to be movement; the eye, in changing fixation from one light to another, or from one part of the figure to another, has the first one or part to use as a reference.

The autokinetic illusion is most apt to occur in night formation flying when only one wing-tip light is seen. One remedy would be to install several lights or a lighted line on the wingtips. Sufficient acquaintance of pilots with this phenomenon may be more practical and satisfactory than further complicating aircraft equipment.

---

*A still more satisfactory quantity, the attenuation length, has been recently proposed. It is the distance over which contrast is reduced to 1/e of its inherent value.

The oculogyral illusion consists of an illusory movement and displacement of objects subsequent to rotation of the head. It is due to stimulation of the vestibular apparatus, the semi-circular canals. Following rapid, prolonged rotation in one direction, objects appear to be both moving and displaced in the opposite direction. Following this there is an apparent movement of objects and displacement in the direction of the head movement. The apparent movement and displacement is due to a nystagmus induced by the rotation. In daylight, relatively fast acceleration of rotation is required before illusory effects are induced. However, in the dark, the threshold for apparent motion follows as little as 0.2 to 0.3 degree (one study recorded 0.12 degree) of rotary acceleration per second per second. In flying at night the effects may be induced by tight turns, particularly when the turns are rapid and are prolonged. Spins may induce the effect at night, or in the day when the spins are rapid and prolonged.

The series of apparent reversing rotation and displacements is not attained unless there are about 20 rotations at 25 rpm. However, illusions of rotation and displacement do occur with much less stimulation. Studies have shown that there is no habituation to the oculogyral illusion.

The coriolis acceleration occurs in an oculogyral illusion that has the complicating factor that the position of the head is changed between the stimulus rotation and the illusory response. It is particularly dangerous because it is so confusing to the pilot. It has apparently been the cause of a certain number of unexplained aircraft accidents, particularly in jet fighters.

An example of the production of this illusion is as follows: After take-off, a jet fighter pilot started a steep bank to the left. At the time he started into the bank he also turned his head downward to the left to operate a console control. If he had not moved his head after the bank was made, vestibular stimulation would have told him that he was coming out of the bank. His visual reference would have overridden this stimulation to a certain extent. However, when he turned his head down to the left, he lost outside visual reference, and the stimulation of the bank was as if he were going over on his face, so when he turned his head back to the forward position, the aircraft appeared to be climbing into a loop.

The oculogravic illusion occurs following moderately high acceleration. It is an illusory effect of viewed objects rising when the individual is undergoing acceleration. Since he has to harmonize his position with viewed objects, he feels that he is lying on his back. This illusion is considered to be caused by stimulation of the otolith. This illusion is less dangerous than the oculogyral because high accelerative stimulation is necessary to induce it, and the inducing maneuver and the type of disorientation are less likely to result in loss of control of the aircraft.

The remedy for these illusions is to refer almost continuously to attitude instruments and to rely on them when flying jet fighters. It is difficult to refer to attitude instruments continuously during formation flight. A certain number of severe aircraft accidents have evidently resulted from this difficulty. The solution appears to be the development of an attitude indicator to be projected on the side panels or made otherwise observable while watching the lead ship in a formation.

Whiteout

As more and more lanes and airbases are developed along great circle routes a special problem arises for the pilots who must fly over barren, snow-covered areas, as in the Arctic and especially the Antarctic. The problem was recognized as serious some time ago by Army personnel. It is produced by the fact that under certain atmospheric and illumination conditions no contrast is provided in the environment, so that all objects, as well as the horizon, are lost in an apparently homogeneous field. With the horizon gone and no shadows or brightness differences produced by variations in terrain, Army personnel found themselves driving vehicles over the edges of crevices or into great banks of snow.

The problems that whiteout produces in flight operations are clearly most serious in take-off and landing, especially under emergency conditions when no artificial aids are available, and in any attempt to fly by VFR.

Although whiteout is extremely hazardous, no satisfactory means of beating the problem has been worked out. The hazard might be somewhat reduced by projecting a grid on a light beam from vehicles or aircraft, so that changes in terrain upon which the grid was projected would produce distortions in the grid. However, the power requirements of the system might limit its usefulness.

LIST OF REFERENCES

VISION THROUGH THE WINDSHIELD AND CANOPY

9-1 Anon. F-100A Human Factors Report No. 4. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. (CONFIDENTIAL)

9-2 Anon. Preliminary Human Factors Evaluation of the YF-102 All Weather Interceptor. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. (CONFIDENTIAL)

9-3 Anon. Second Letter Report on Human Factors Evaluation of F-84 Airplane. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. (CONFIDENTIAL)

9-4 Anon. Visibility from the Rear Cockpit of T-33 Aircraft (1-1-52 to 12-31-53). Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. (CONFIDENTIAL)

9-5 Brown, F. R., et al., The Development of Inspection Methods and Criteria for Optical Distortion in Cockpit Enclosures. Report TED No. NAM AE-4505. May 17, 1954.

9-6 Calvert, E. S., Royal Aircraft Establishment, Farnborough, England. Report No. E1. 1472. February 1950. (CONFIDENTIAL)

9-7 Cibis, P. A., "Retinal Adaptation Applicable to Visual Problems in Flight at Increasing Altitudes." In. Clayton S. White (Editor), Physics and Medicine of the Upper Atmosphere: A Study of the Aeropause. University of New Mexico Press, Albuquerque, N. M. 1952.

9-8 Cibis, P. A., and Haber, F., Studies on Effects of Windshields and/or Air of Different Densities in Stereoscopic Vision. I. School of Aviation Medicine, Randolph Field, Texas. November 1950.

9-9 Craik, K. J. W., A Note on Windscreen Design and Visibility from Fighter Aircraft. Great Britain, Psychol. Lab., Cambridge University. November 1941.

9-10 Cross, H. F., Final Report on Tests of Effectiveness of Reflection-Reducing Coating in Reducing Flash from Aircraft Plastic Surfaces. Naval Air Station, Patuxent River, Md. Project TED No. PTR-2539. November 17, 1944.

9-11 Edwards, T. M., Development of a Photographic Instrument for Measuring Aircraft Cockpit Visibility Limits. CAA Tech. Devel. Report No. 153. Civil Aeronautics Administration, Indianapolis, Ind. January 1952.

9-12 Edwards, T. M., and Howell, W. D., Recommendations on Cockpit Visibility Standards for Transport Type Aircraft. CAA Tech. Devel. Report No. 275. Civil Aeronautics Administration, Indianapolis, Ind. February 1956.

9-13 Edwards, T. M., and Howell, W. D., A Study of Pilots' Eye Movement During Visual Flight Conditions. CAA Tech. Devel. Report No. 179. Civil Aeronautics Administration, Indianapolis, Ind. January 1952.

9-14 Emerson, G. O., Effect of Retinal Blind Spot and Conspicuity. CAA-IES Mid-Air Collision Symposium, Indianapolis, Ind. November 1955.

9-15 Glover, H. C., Light Transmission and Haze Requirements for Transparent Enclosures. WADC Tech. Report No. 55-55. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. April 1955.

9-16 Hall, M. V., and Greenbaum, L. J., Areas of Vision and Cockpit Visibility. Civil Aeronautics Administration. 1949.

VISION THROUGH THE WINDSHIELD AND CANOPY (Cont)

9-17 Howell, W. D., and Edwards, T. D., Determination of Some Geometric Relationships Relative to Collision Flight Paths. CAA Tech. Devel. Report No. 259. Tech. Devel. and Eval. Center, Indianapolis, Ind. June 1955.

9-18 Luczak, A., Note on Vision through Glass. Great Britain, FPRC Report No. 525. April 1943. (CONFIDENTIAL)

9-19 Naish, J. M., and Webb, E. R., Tech. Note No. IAP 1008. Great Britain, Royal Aircraft Establishment, Farnborough, England. January 1952. (CONFIDENTIAL)

9-20 Olenski, Z., Pohocki, and Aastuis., Limiting Dimensions of Cockpit Framing Based on Geometry of Binocular View. Aero 2095. Great Britain, Royal Aircraft Establishment, Farnborough, England. November 1945.

9-21 Pigman, G. L., and Edwards, T. M., Airline Pilot Questionnaire Study on Cockpit Visibility Problems. CAA Tech. Devel. Report No. 123. Tech. Devel. and Eval. Center, Indianapolis, Ind. September 1950.

9-22 [illegible], E. A., and Chapanis, A., "Visual Factors in the Design of Military Aircraft." J. Aviat. Med. Vol 17. 1946. pp. 115-132.

9-23 Sulzo, P. J., Human Visual Capacities and Limitations as Related to the Mid-Air Collision Hazard. CAA-IES Mid-Air Collision Symposium. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. November 1955.

PERISCOPES FOR PILOTING AIRCRAFT

9-24 Emerson, G. O., Pilot Vision from the Prone Position in Fighter Aircraft. WADC Tech. Report 55-55. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. April 1955.

9-25 Rose, H. W., and Ripple, P. H., Visual Problems of Pilot in Prone Position. USAF School of Aviation Medicine, Project No. 21-24-100, Report No. 1.

9-26 Roscoe, S. N., The Effects of Eliminating Binocular and Peripheral Monocular Visual Cues upon Airplane Pilot Performance in Landing. CADO, Tech. Data Digest. Vol. 14 (12) June 15, 1949. pp. 13-22.

9-27 Vanderplas, James M., The Apparent Size of Objects Viewed through Telescopes. WADC Tech. Report 54-460. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. October 1954.

VISUAL PROBLEMS CAUSED BY HIGH ALTITUDE HELMETS

9-28 Cullen, R. E., Moyle, M. P., and Glover, H. C., WADC Tech. Note 55-352. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. July 1955.

OPTICAL TELESCOPES (BINOCULAR AND MONOCULAR) FOR PILOT USAGE

9-29 Anon. U. S. OSRD-NDRC, OSRD No. 4444. February 10, 1945. (CONFIDENTIAL)

9-30 Anon. The NDRC Binocular Testing Program. Army-Navy-OSRD Vision Committee, 11th Meeting, Minutes and Proceedings. April 10, 1945. pp. 13-15.

9-31 Anon. Final Report: Binocular Developments. Bausch and Lomb Optical Company. December 28, 1944.

LIST OF REFERENCES (Cont)

OPTICAL TELESCOPES (BINOCULAR AND MONOCULAR) FOR PILOT USAGE (Cont)

9-32 Anon. Comparative Trial of Binocular and Visual Search. Great Britain Air/Sea Warfare Devel. Unit, Report No. 48/5. September 29, 1948.

9-33 Anon. Optical Instruments. Summary Report of NDRC, Division 16, Vol. 1. 1946. (pp. 600-604 contain 40 references on binocular design.)

9-34 Anon. Report of the Subcommittee on Design and Use of Binoculars. Army-Navy-OSRD Vision Committee, 12th Meeting, Minutes and Proceedings. June 12, 1945.

9-35 Anon. A Short Statistical Survey of the Variation of Pupil Diameter with Field Brightness. A. R. L/N-2/0.802. Admiralty Research Laboratory, Teddington, England. March 1942.

9-36 Anon. Visibility Studies and Some Applications in the Field of Camouflage. Summary Tech. Report of Division 16. National Defense Research Committee. Vol. 2. 1946.

9-37 Anon. Great Britain Royal Air Force Coastal Command, Memo No. 50. February 12, 1943. (CONFIDENTIAL)

9-38 Blackwell, H. R., "Contrast Thresholds of the Human Eye." J. Opt. Soc. Amer. Vol. 36. November 1946. pp. 624-643.

9-39 Boynton, R. M., and Bush, W. R., Laboratory Studies Pertaining to Visual Air Reconnaissance. WADC Tech. Report 55-304 Part I. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. September 1955.

9-40 Brackett, F. L., Report on Project No. 40 - Military Characteristics of Spectacle Type Binoculars. Medical Research Lab., Fort Knox, Ky. May 31, 1944.

9-41 Chute, E., Bartley, S. H., The Effects of Binocular Magnification on the Visibility of Targets at Low Levels of Illumination. NDRC Sect. 16.1, OSRD Report 4433. November 30, 1944.

9-42 Coleman, H. S., Report on Optical Inspection. U. S. OSRD-NDRC, Div. 16, OSRD Report No. 6103. October 20, 1945.

9-43 Coleman, H. S., and Rosenberger, H. E., "A Comparison of Visual and Photoelectric Measurements of the Attenuation of Brightness Contrast by the Atmosphere." J. Opt. Soc. Amer. Vol. 40. No. 6. June 1950. pp. 371-372.

9-44 Coleman, H. S., and Verplank, W. S., "A Comparison of Computed and Experimental Detection Ranges of Objects." J. Opt. Soc. Amer. Vol. 38. No. 3. March 1948. pp. 250-253.

9-45 Coleman, H. S., Armed Forces NRC Vision Committee, 33rd Meeting. Confidential Report is published by the Executive Secretariat. (This report contains 112 references covering all phases of binocular design.) November 12, 1953.

9-46 Duntley, S. Q., "Reduction of Apparent Contrast by the Atmosphere." J. Opt. Soc. Amer. Vol. 36. 1946. p. 359A.

9-47 Duntley, S. Q., "The Visibility of Distant Objects." J. Opt. Soc. Amer. Vol. 38. March 1948. pp. 237-249.

9-48 Hardy, A. C., "Atmospheric Limitations on the Performance of Telescopes." J. Opt. Soc. Amer. Vol. 36. No. 5. May 1946. pp. 283-287.

9-49 Hardy, A. C., and Perrin, F. H., The Principles of Optics. McGraw-Hill Book Company Inc., New York, N. Y. 1932.

LIST OF REFERENCES (Cont)

OPTICAL TELESCOPES (BINOCULAR AND MONOCULAR) FOR PILOT USAGE (Cont)

9-50 Jacobs, D. H., Fundamentals of Optical Engineering. McGraw-Hill Book Company, Inc., New York, N. Y. 1943.

9-51 Jenkins, F. A., and White, H. E., Fundamentals of Optics. McGraw-Hill Book Company, Inc.

9-52 Lamar, E. S., USN OEG Study No. 250(LO)006-46. (CONFIDENTIAL)

9-53 Leavitt, D. F., USN, BuAer Preliminary Report on TED No. UML 25159. May 6, 1945.

9-54 Miller, C. W., and Beck, L. H., The Effects of Night Binocular Design Features on the Visibility of Targets at Low Levels of Illumination. Brown University, OSRD Report No. 6136. October 25, 1945.

9-55 Riggs, Lorrin A., Summary of Information on Relative Efficiency of Monocular and Binocular Optical Instruments. Minutes and Proceedings of the Army-Navy-NRC [illegible]

9-56 Smith, T., Experimental Studies of the Use of Binoculars at Night. Nat. Phys. Lab. November 16, 1943.

9-57 Verplanck, W. S., Field Tests of Optical Instruments. NAVORD Report 77-46. Bur. of Ord. Publication. March 15, 1947.

METEOROLOGICAL CONDITIONS AND TIME OF DAY

9-58 Binford, F., "Duration and Intensity of Sunshine." General Electric Research Lab., Illum. Engng. Vol. 43. July 1948.

9-59 Blackwell, H. R., Report on the Roscommon Visibility Tests. Minutes and Proceedings of the Armed Forces-NRC Vision Committee, 23rd Meeting. March 4-5. 1949. pp. 107-122.

9-60 Brown, D. R. E., Natural Illumination Charts. USN, BuShips, Research Div. Project NS714-100, Report No. 374-1. September 1952.

9-61 Christensen, J. M., Some Typical Sky and Earth Brightness at Altitudes 10,000 to 40,000 ft and their Relationship to the Eye Adaptation Problems of the Radar Operator. AMC Memo. Report No. TSEAA-694-11. December 9, 1946.

9-62 Dukelman, L., Horizontal Attenuation of Ultraviolet and Visible Light by the Lower Atmosphere. Naval Research Lab. Report No. 4031. September 10, 1952.

9-63 Duntley, S. Q., "Reduction of Apparent Contrast by the Atmosphere." J. Opt. Soc. Amer. Vol. 38. February 1948. pp. 179-191.

9-64 Duntley, S. Q., "The Visibility of Objects Seen Through the Atmosphere." J. Opt. Soc. Amer. Vol. 36. 1946. p. 359A.

9-65 Duntley, S. Q., "Reduction of Contrast by the Atmosphere." J. Opt. Soc. Amer. Vol. 36. 1946. p. 259A.

9-66 Duntley, S. Q., "The Visibility of Distant Objects." J. Opt. Soc. Amer. Vol 38. March 1948. pp. 237-249.

LIST OF REFERENCES (Cont)

METEOROLOGICAL CONDITIONS AND TIME OF DAY (Cont)

9-67 Festinger, L., ONR Report No. 151-1-14. April 15, 1948. (CONFIDENTIAL)

9-68 Garbell, M. A., "The Visual Range in Daylight, Darkness, and Twilight." Garbell Research Foundation, Garbell Aeronautical Series No. 6. 1952.

9-69 Hill, N. E. G., Tests on the Recognition of Coloured Light Signals which are Near the Limit of Visibility. RAF Report No. E&I 1159. 1939.

9-70 Hopkinson, R. G., "Measurements of Sky Luminance Distribution at Stockholm." J. Opt. Soc. Amer. Vol. 44. 1954. p. 44.

9-71 Lamar, E. S., USN OEG Study No. 250 (LO) 006-46. (CONFIDENTIAL)

9-72 Langstoth, G.O., et al., "A Laboratory Study of Visibility through Clouds." Canada J. Res. Vol. 25a. 1947. pp. 49-57 and 58-61.

9-73 MacAdam, D. L., "Visual Sensitivities to Color Difference in Daylight." J. Opt. Soc. Amer. Vol 32. 1942. pp. 247-274.

9-74 Middleton, W. E. K., Vision Through the Atmosphere. University of Toronto Press, Toronto, Canada. 1952.

9-75 Packer, D., and Lock, C., The Brightness and Polarization of the Daylight Sky at Altitudes of 18,000 to 38,000 feet Above Sea Level. ONR, NRL, Report No. 3713. July 31, 1950.

9-76 Tousey, R., and Hulburt, O., "Brightness and Polarization of the Daylight Sky at Various Altitudes Above Sea Level." J. Opt. Soc. Amer. Vol. 37. 1947. pp. 78-92.

GENERAL BIBLIOGRAPHY

9-77 Anon. U. S. Office of Scientific Research and Development, National Defense Research Committee. OSRD No. 1709. June 15, 1943. (University of Rochester)

9-78 Anon. "Annual Report. Part I. Equipment and Procedure for Photometric Measurements of Blackout and Dimout Luminaries. Part II. Description of Methods for Measuring Atmospheric Transmission." Illum. Engng. Vol. 38. 1943. pp. 509-514, 5-15-517.

9-79 Anon. U. S. Office of Scientific Research and Development, National Defense Research Committee. OSRD No. 4183. Technicolor Motion Picture Corp. February 28, 1945. (CONFIDENTIAL)

9-80 Anon. Characteristics of the Earth's Atmosphere. Douglas Aircraft Company, Inc. U.S.A.F. Winter, 1954.

9-81 Anon. Great Britain Flying Personnel Research Committee, Vision Committee, Dazzle Subcommittee. Great Britain. OSRD WA-319-2. October 27, 1942. (CONFIDENTIAL)

9-82 Anon. Final Report on Project OP/V60/A16-3(17). U. S. Navy Atlantic Fleet Operational Development Force, U. S. Naval Base, Norfolk, Va. July 24, 1951. (CONFIDENTIAL)

9-83 Anon. Distribution Curves of Atmosphere Transmission for Continental United States. U. S Coast Guard, Civil Engineering Div. December 1950.

9-84 Anon. Field Tests of Optical Instruments. U. S. Navy, Bureau of Ordnance Report No. 77-46. March 15, 1947.

9-85 Anon. Book of Reference 797, Handbook on Look-Outs and Service Optical Instruments. Great Britain Admiralty. OSRD No. WA [illegible]. [illegible].

9-86 Anon. Great Britain War Office, Army Operational Research Group. Report No. 165. June 1944.

9-87 Anon. Night Visibility. U. S. National Academy of Sciences, National Research Council. 1954.

9-88 Anon. Night Vision for Airmen. U. S. Navy, Office of Naval Research, Aviation Div. August 1944.

9-89 Anon. Factors Affecting Night Binoculars. Army, Navy-OSRD Vision Committee 11th Meeting. April 10, 1945. p. 14.

9-90 Anon. Farrand Optical Company. Engineering Report No. 276. July 1954. (CONFIDENTIAL)

9-91 Anon. Optical Viewing Devices for Aircraft. WADC Tech. Report 52-254. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. January 1953. (CONFIDENTIAL)

9-92 Anon. Optical Viewing Devices for High Performance Aircraft. Farrand Optical Company. Engineering Report No. 227. October 1952. (CONFIDENTIAL)

9-93 Anon. U. S. Office of Scientific Research and Development. National Defense Research Committee, OSRD No. 4181. February 28, 1945. (CONFIDENTIAL)

9-94 Anon. Report No. 93.Great Britain. OSRD No. WA-2036-6. Royal Air Force, Bomber Command, Central Night Vision Training School. March 9, 1944. (CONFIDENTIAL)

9-95 Anon. Report on Binocular Developments. Bausch and Lomb Optical Company. December 28, 1944.

9-96 Anon. U. S. Office of Scientific Research and Development, National Defense Research Committee, OSRD No. 1085. U. S. Office of Emergency Management. December 15, 1942.

9-97 Anon. Some Factors that Limit Vision. U. S. Navy, Office of Naval Research. September 1951.

9-98 Anon. The Spectral-Transmissive Properties of Plastics for Use in Eye Protection. American Standards Association, Inc.

9-99 Anon. Stray Light in Optical Systems. U. S. Navy, Bureau of Ordnance Report No. 437. NAVORD Report 437. 1948.

9-100 Anon. Studies in Visual Acuity. U. S. Army, Adjutant General's Office, U. S. Government Printing Office Personnel Research Service Report No. 742. 1948.

9-101 Anon. Summary of Flight Evaluation of the Bausch and Lomb Periscope. Edwards Air Force Base Flight Test Center. (Letter from Edwards to WCRDF-4, Aero Medical Lab. WADC, dtd March 15, 1955). (CONFIDENTIAL)

9-102 Anon. Tests of Binoculars. U. S. Office of Emergency Management OEMsr-1229. (Brown University), January 1, 1945.

9-103 Anon. U. S. Office of Scientific Research and Development, National Defense Research Committee, OSRD No. 6552. Tiffany Foundation. April 10, 1946.

9-104 Anon. Trials of Coloured and Neutral Filters. Great Britain War Office, Army Operational Research Group. OSRD No. WA-3032A. May 3, 1943.

9-105 Alluisi, E. A., Harker, G. S., Enoch, J. M. et al., Binocular Stereoptic Acuity and Spatial Localization as Criteria for the Evaluation of Contact Lenses. AMRL Project 6-95-20-001 and 6-64-12-028, Report 7C. Office of Surgeon General Army Medical Research Lab., Fort Knox, Ky. December 1951.

9-106 Alluisi, E. A., Inaba, K., and Nungesser, F. L., Jr., Changes in Visual Depth Perception with the Wearing of Contact Lenses. Report 105. Dept. of the Army, Office of Surgeon General, Fort Knox, Ky. December 1952.

9-107 Alpern, M., A Study of Some Aspects of Metacontrast. Abstracts of Doctoral Dissertations, No. 64. Ohio State University Press. 1953.

9-108 Ashton, Imus H. A., and Graybiel, A., "Visual Illusions in Night Flying." Amer. J. Ophthal. Vol. 34. May 1951. p. 35.

9-109 Bailey, W. R., Report on 6 × 42 Plastic Binocular. U. S. Naval Observatory Report No. 644. July 1, 1944.

9-110 Barr, N. L., Murray, J. F., Murray, R. D., Hussman, T. A., and Parker, J. F., Brightness of the Atmosphere; Effects of Cloud Conditions. Naval Medical Research Inst. (NMRI) 11: 1011-1116 Research Report. Project NM 001 056.07.02. October 20, 1953.

9-111 Bartlett, N. R., The Discrimination of Two Simultaneously Presented Brightnesses. 1942.

9-112 Bartley, S. H., and Chute, E., The Effects of Binocular Magnification on the Visibility of Targets at Low Levels of Illumination. U. S. Office of Scientific Research and Development, National Defense Research Committee. OSRD No. 4433. November 30, 1944.

9-113 Beck, L. H., An Engineering Approximation to Visual Luminance Discrimination Data for Use in Evaluating Optical Aids. University of Michigan Vision Research Lab., Optics and Vision Group. August 7, 1955.

9-114 Beck, L. H., An Experimental Study of Galilean Telescopic Spectacles. University of Michigan Vision Research Lab., Optics and Vision Group. June 2, 1955.

9-115 Beck, L. H., Experimental Evaluation of the Elgeet Image-Stabilized Binoculars for Tank Use. University of Michigan Vision Research Lab., Optics and Vision Group. May 24, 1955.

9-116 Beck, L. H., An Experimental Investigation of Binoculars as an Aid to Night Vision. 1945.

9-117 Benford, F., and Bock, J. E., A Time Analysis of Sunshine. 1938.

9-118 Best, L. A., Optical Properties of Plexiglass. Douglas Aircraft Company, Inc. Process Tech. Bull. No. PTB-TU-126. December 11, 1944.

9-119 Bierman, J. A., and Schindler, A. F., Evaluation of Two Pairs of Heated Goggles. U. S. Nat. Inst. of Health, Div. of Industrial Hygiene. July 19, 1943. (CONFIDENTIAL)

9-120 Blackwell, H. R., Visual Detection at Low Luminance through Optical Filters. Highway Research Board Bull. 89. National Research Council, Washington, D. C. January 1954. pp. 43-62.

9-121 Blum, H. F., Solar Energy Reaching the Retina: Proposed Spectral Curve for Testing Sun Scanning Glasses. Army-Navy-OSRD Vision Committee. July 27, 1944. pp. 13-23. Also issued as report of Naval Medical Research Inst., Bethesda, Md. Med. Project X-416. August 1, 1944. (CONFIDENTIAL)

9-122 Brackett, F. S., Military Characteristics of Spectacle Type Binoculars. Project No. 40. U. S. Army Service Forces, Armored Medical Research Lab., Fort Knox, Ky. May 30, 1944.

9-123 Bray, C. W., Note re Fixed-Focus Optical Devices. Army-Navy-OSRD Vision Committee. Minutes of the Tenth Meeting. March 13, 1945. p. 16.(CONFIDENTIAL)

9-124 Brown, C. W., Ghiselli, E. E., Jarrett, R. F., and Minium, E. W., Comparative Effectiveness of Speed of Detection of Visual Stimuli in the Prone and Seated Positions. USAF, Air Materiel Command, Aero Medical Lab. Engineering Div Wright-Patterson Air Force Base, Dayton, Ohio. May 1948.

9-125 Brown, R. H., Imus, H., Niven, J. I., and Graybiel, A., The Relationship between Apparent Displacement and Motion in the Oculogyral Illusion. Project NM001 003. U. S. School of Aviation Medicine and Research. May 1, 1949.

9-126 Brown, R. H., Imus, H. A., River, J. I., and Graybiel, A., The Relationship between Apparent Displacement and Motion in the Oculogyral Illusion. Project No. NM140-255. May 1, 1949.

9-127 Byram, G. M., "Filters for Penetrating Atmospheric Haze." J. Forestry. Vol. 40. No. 7. July 1942. pp. 530-532.

9-128 Camp, B. H., and Moran, H. S., Multiple Scattering of Light: Visibility in Cloud and Fog. Wesleyan University, Ordway Lab., Windsor Locks, Conn. September 1954.

9-129 Campbell, P. A., "Atmospheric Characteristics of Greatest Human Significance in Aviation of the Next Decade." Aero Engng. Rev. Vol. 12 (4). 1953. pp. 50-55.

9-130 Campbell, C. J., Capt. USAF, McEachern, L. J., Capt. USAF, Marg, E., Lt. Col. USAF, Flight by Periscope. WADC Tech. Report 55-142. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.

9-131 Carroll, C. C., Wallhausen, C. W., et al., Radioactive Activator and Phosphor Combinations for the Illumination of Reticles in Optical Instruments. Navy Dept. Bureau of Ordnance. October 1947.

9-132 Chapanis, A., Rotoformed Plastic Bubble Canopies. Memo Report. U. S. Army Air Forces, Air Tech. Service Command. Engineering Div. Aero Medical Lab. August 31, 1945.

9-133 Chapanis, A., Summary and Evaluation of the Status of Research on the Effect of the Optical Quality of Transparent Aircraft Panels on Vision. U. S. Army Air Forces, Air Materiel Command. Engineering Div. Aero Medical Lab. Ser. No. TSEAA-696-93. August 2, 1946.

9-134 Chapanis, A., Transmission Characteristics of Green Plastic Canopies for the P-51-D. U. S. Army Air Forces, Materiel Command. Engineering Div. Aero Medical Lab. August 18, 1944.

9-135 Chapanis, A., Schachter, S., Visual Effectiveness of Low Reflectance Coatings Applied to Transparent Areas of Aircraft. U. S. Army Air Forces, Air Tech. Service Command. Engineering Div. Aero Medical Lab. Ser. No. TSEAL3-695-62. October 31, 1945.

9-136 Chapanis, A., and Schachter, S., Depth Perception through a P-80 Canopy and through Distorted Glass. U. S. Army Air Forces, Air Tech. Services Command, Engineering Div., Aero Med. Lab., Ser No. TSEAL3-695-48N. October 22, 1945.

9-137 Cocquyt, P., "Sensory Illusions." Shell Aviation News. No. 175. 1952.

9-138 Coleman, H. S., Studies of Atmospheric Attenuation of Brightness Contrast at the University of Texas from March 1949 through November 1949. ORL/UT Special Report No. 2. November 12, 1949.

9-139 Coleman, H. S., The Contrast Rendition of Optical Instruments. Apparatus and Procedure Report No. 3, Draft Copy. U. S. Naval BuOrd, Pennsylvania State College. April 30, 1946.

9-140 Coleman, H. S., and Clark, D. G., Photoelectric and Photographic Procedures for the Evaluation of Optical Instrument Design. OSRD No. 6107. U. S. Office of Scientific Research and Development, National Defense Research Committee. October 16, 1945.

9-141 Coleman, H. S., Coleman, M. F., Clark, D. G., and Harding, S. W., A Method for Predicting the Range at Which Targets are Detectible through Visual Telescopic Systems. NAVORD Report 436. July 1947.

9-142 Craik, K. J. W., Great Britain. OSRD No. WA-3499-2d.

9-143 Crawford, W. A., Forward Vision in Future Aircraft. RAF F.P.R.C. 869. March 1954.

9-144 Crumley, L. M., Atkinson, W., and Fletcher, D. E., The Development of Inspection Methods and Criteria for Optical Distortion in Cockpit Enclosures. Report TED NAM AD-4406, Part 2. Aer. Med. Equip. Lab., Naval Air Exp. Station, Naval Air Materiel Center. June 25, 1954.

9-145 Dill, D. B., Tests of Flyers' Headgear Assemblies. U. S. Army Air Forces, Materiel Center, Engineering Div., Aero Med. Lab. January 11, 1943.

9-146 Dunham, T., Jr., Studies of Visual Telescope System Employing Reflection Optics. Armed Forces National Research Council Vision Committee. February 1951.

9-147 Dunoyer, L., "On the Perception of the External World by Monocular or Binocular Vision, with or without Instruments." Rev. Opt. (Theor. Instrum.). Vol. 19. 1940. pp. 177-190.

9-148 Edwards, T. M., Development of an Instrument for Measuring Aircraft Cockpit Visibility Limits. CAA Tech. Report No. 183. Civil Aeronautics Administration, Indianapolis, Ind. June 1952.

9-149 Farnsworth, D., Inspection Goggle for Checking Visibility Spectral Quality of Lighting for Dark Adaptation. Report No. 170. Vol. 10. BuMed, Medical Research Lab., U. S. N. Submarine Base, New London, Conn. March 15, 1951. pp. 1-17.

9-150 Fisher, M. B., "The Relationship of the Size of the Surrounding Field to Visual Acuity in the Fovea." J. Exp. Psychol. Vol. 23. 1938. pp. 215-238.

9-151 Foitzik, L., The Contrast Threshold of the Eye with Relation to the Problem of Visibility. Publications of the Meteorological Service of the German Democratic Republic, No. 8. Akademie Verlag, Berlin. Translated from German by J. M. Lotze. 1951.

9-152 Fry, G. A., A New Method of Producing Continuously Variable Magnification with an Optical System. WADC Tech. Report 52-270 Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. October 1952.

GENERAL BIBLIOGRAPHY (Cont)

9-153 Goldie, E. A., A Device for the Measurement of Light Scattered by Perspex and Other Transparent Materials. Report No. 551. Great Britain, Flying Personnel Research Committee. October 20, 1943. OSRD Liaison Office Ref. No. II-5-6398.

9-154 Goldie, E. A. G., Transmission Data on British and U. S. Red Dark Adaptation Goggles. Great Britain, RAF Physiol. Lab., Farnborough, England. November 1944.

9-155 Graybiel, Ashton, and Brown, R. H., The Delay in Visual Reorientation Following Exposure to a Change in Direction of Resultant Force on a Human Centrifuge. Project No. NM001 037, Joint Project Report No. 3. U. S. Naval Air Station School of Aviation Medicine and Research, Pensacola, Fla. Project No. NR 140-455. Tulane University.

9-156 Graybiel, A., Clark, B., The Autokinetic Illusion and It's Significance in Night Flying. Project No. X-148 (Av-4-3). Report 3. February 7, 1945.

9-157 Graybiel, A., and Hupp, D. I., The Oculogyral Illusion. Project No. X-148 (Av-4-3). Report 4. November 1, 1945.

9-158 Graybiel, A., Kerr, W. A., and Bartley, S. H., "Stimulus Thresholds of the Semicircular Canals as a Function of Angular Acceleration." Amer. J. Psychol. Vol. 61. January 1948. pp. 21-36

9-159 Guedry, F. E., Jr., "The Effect of Visual Stimulation on the Duration of Postrotational Apparent Motion Effects." J. Gen. Psychol. Vol. 43. 1950. pp. 313-322.

9-160 Guedry, F. E., Jr., and Niven, J. I., Interaction of Vestibular Stimuli of Different Magnitudes and Opposite Directions. Part I. Perception of Visual Apparent Motion During Angular Accelerations. Project No. NM 001 063.01.36. Joint Report No. 36. U. S. Naval Air Station School of Aviation Medicine and Research, Pensacola, Fla. December 8, 1954.

9-161 Guth, S. K., Fixed-Focus Binoculars and Telescopes. Army-Navy-OSRD Vision Committee, Minutes of the Sixth Meeting. October 12, 1944. pp. 9-13. (CONFIDENTIAL)

9-162 Hartline, H. K., and Beall, D., Jr., Optical Distortion in Airplane Windshields. U. S. Office of Scientific Research and Development, Committee on Medical Research, U. S. Office of Emergency Management Contract OEMcmr-300. University of Pennsylvania. November 1945.

9-163 Hartline, H. K., Wagman, I. H., Milne, L. J., et al., Physiological Factors Determining the Performance of Night Binoculars. OSRD No. 6069. U. S. Office of Scientific Research and Development, National Defense Research Committee. University of Pennsylvania. October 31, 1945.

9-164 Hewson, E. W., "Weather and Atmospheric Pollution." Weatherwise. October 1950. pp. 103-107.

9-165 Hicks, W. E., An Aspect of Searching with Binoculars. Great Britain Medical Research Council. Appl. Psychol. Research Unit. A.P.U. 140/50, Psychological Lab., Cambridge, England. September 1950.

9-166 Hulburt, E. O., The Brightness and Polarization of the Daylight Sky. Report N-3257. Naval Research Lab. February 1948.

9-167 Imus, H. A., Graybiel, A., Brown, R. H., and Niven, J. I., "Visual Illusions in Night Flying." Proc. Assoc. Res. Ophthal. 19th Meeting. June 1950. pp. 35-41.

9-168 Ingarden, R. S., and Ochman, H., Optimal Optical Systems. 1954.

9-169 Judd, D. B., Standard Color Filters for Electronics Equipment. Armed Forces National Research Council Vision Committee. July 1, 1952.

9-170 Kasperelt, O. K., Designing of Optical Systems for Telescopes. Ordnance Tech. Note No. 14. U. S. Army Service Forces, Office of Chief Ordnance Officer. February 1933.

9-171 King, P., Report No. P-2008. U. S. Naval Research Lab. February 27, 1943. (CONFIDENTIAL)

9-172 Kinney, J. A. S., and Pratt, C. H., The Effect of Refractive Error on Acuity through Binoculars. Report No. 245. No. 6. Medical Research Lab., U. S. Naval Submarine Base, New London, Conn. April 2, 1954.

9-173 Koch, W. R., Methods for the Determination of Optical Quality of Transparent Materials. U. S. Army Air Forces, Materiel Command, Engineering Div., Materials Lab. October 29, 1943.

9-174 Kristofferson, A. B., Preliminary Study of Comparative Detection Ability between Monocular and Binocular Vision. Project No. 2144-849-M. Research Report 24. University of Michigan Vision Research Lab., Optics and Vision Group. August 31, 1955.

9-175 Kuhl, A., Zur Verbesserung der Nachtsicht aus dem Flugzeug durch Fernrohr. (Toward Improving Night Vision from an Airplane with a Telescope) German Aircraft Research Report No. 1738/4. Friedrich Schiller Universitat Jena. December 17, 1944.

9-176 Leyzorek, M., A Hand-Held Instrument for Measuring Visual Fields from Aircraft. U. S. Army Air Forces, Air Tech. Service Command, Engineering Div., Aero Medical Lab. April 11, 1945.

9-177 Leyzorek, M., and Romejko, W. J., Fields of Vision from Fighter Aircraft. U. S. Army Air Forces, Air Tech. Service Command, Engineering Div., Aero Medical Lab. June 7, 1945.

9-178 Leyzorek, M., and Rouse, R. O., Comparison of Visual Field Restrictions by Five Types of Flying Goggles. U. S. Army Air Forces, Materiel Command, Engineering Div., Aero Medical Lab. July 10, 1944.

9-179 London, H., Binoculars for Night Use. U. S. Navy, BuAer. 1945. (CONFIDENTIAL)

9-180 Middleton, W. E. K., "The Attenuation of Contrast by the Atmosphere." Photogrammetric Engng. N.R.C. No. 2263. National Research Council of Canada. December 1950. pp. 663-672.

9-181 Middleton, W. E. K., and Mungall, A. G., "The Luminous Directional Reflectance of Snow." J. Opt. Soc. Amer. Vol. 42. August 1952. pp. 572-579.

9-182 Middleton, W. E. K., and Mungall, A. G., "On the Psychophysical Basis of Meteorological Estimates of 'Visibility'." Trans. Amer. Geophysical Union. Vol. 33. August 1952. pp. 507-512.

9-183 Miles, W. R., Methods of Using Binoculars. From the Minutes and Proceedings of the Armed Forces - NRC Vision Committee. Contract N7-onr 288, T.O.V. Project NR 142-497. November 16-17, 1951. ONR, Lab. of Physiological Psychol., Dept. of Psychology, Yale University.

9-184 Miller, James W., and Bartley, S. H., "A Study of Object Shape as Influenced by Instrumental Magnification." J. Gen. Psychol. Vol. 50. 1954. pp. 141-146.

9-185 Orlansky, J., "The Effect of Similarity and Difference in Form on Apparent Visual Movement." Arch. Psychol. No. 246. 1940.

9-186 Pinson, E. A., Visual Functions. U. S. Army Air Forces, Materiel Div., Experimental Engineering Section. April 9, 1941.

9-187 Pinson, E. A., Airsickness, Its Cause and Prevention. U. S. Army Air Forces, Materiel Div. Experimental Engineering Section. July 31, 1940.

9-188 Pinson, E. A., and Leyzorek, M., Fogging Characteristics and Visual Fields of Flying Goggles. U. S. Army Air Forces, Materiel Command. Engineering Section. Aero Medical Lab. July 10, 1944.

9-189 Prentice, W. C. H., Krimsky, J., and Barker, S., "The Roles of Pattern and Apparent Distance in Determining the Color of Areas Seen through Transparencies." J. Exp. Psychol. Vol. 42. 1951. pp. 201-206.

9-190 Pritchard, B. S., Design and Construction of a Portable Transmissiometer for Atmospheric Optic Studies. Project No. 2144-817-M. Research Report 18. University of Michigan Vision Research Lab., Optics and Vision Group. June 30, 1955.

9-191 Pritchard, B. S., Design and Construction of a Recording Pol Nephelometer for Atmospheric Optics Studies. Project No. 2144-809-M. Research Report 14. University of Michigan Vision Research Lab., Optics and Vision Group June 27, 1955.

9-192 Ratoosh, P., and Graham, C. H., "Areal Effects in Foveal Brightness Discrimination." J. Exp. Psychol. Vol. 42. December 1951. pp. 367-375.

9-193 Riggs, Lorrin A., The Design and Use of Optical Instruments. 1949.

9-194 Romejko, Walter J., Visibility Under Simulated Rain Conditions in Flight. U. S. Army Air Forces, Air Tech. Service Command. Engineering Div., Aero Medical Lab. Ser. No. TSEAL3-695-481. August 4, 1945.

9-195 Roper, V. J., Nighttime Seeing through Heat-Absorbing Windshields. Highway Research Board Bull. Vol. 68. National Research Council, Washington, D. C. January 1953. pp. 16-31.

9-196 Roscoe, Stanley N., Flight by Periscope. I. Inst. of Aviat. University of Illinois, Urbana, Ill.

9-197 Roscoe, S. N., "Designing the Cockpit for High-Speed Flight." Aeronaut. Engng. Rev. Vol. 13. 1954. pp. 47-58.

9-198 Roscoe, Stanley N., and Easler, Scott G., Flight by Periscope. II. Report No. 71-16-9. Office of Naval Research, Special Devices Center. 1952. (CONFIDENTIAL)

9-199 Rose, H. W., Luminance of the Horizon and Dark Adaptation During Meteorological Visibility Observations. Project 21-24-008. Report 1. USAF School of Aviation Medicine, Randolph Field, Texas. July 1950.

9-200 Rouse, Richard O., Restriction of Visual Fields Caused by Various Goggle-Oxygen Mask Combinations. U. S. Army Air Forces, Materiel Command, Engineering Div. Aero Medical Lab. October 6, 1944.

9-201 Saucier, Walter J., Principles of Meteorological Analysis. University of Chicago Press. Chicago, Ill. 1955.

9-202 Schachter, Stanley, and Chapanis, A., Distortion in Glass and Its Effect on Depth Perception. U. S. Army Air Forces, Air Tech. Service Command. Engineering Div., Aero Medical Lab. April 27, 1945.

9-203 von Schelling, H., Thickness Adjustments of Glass Filters to Given Total Transmittance. BuMed Project NM 003 041.40.02. Report 193. Medical Research Lab., U. S. Naval Submarine Base, New London, Conn. March 1952.

9-204 von Schelling, Hermann, A Method for Calculating the Effect of Filters on Color Vision. Report No. 148. Vol. 8. Medical Research Lab., U. S. Naval Submarine Base, New London, Conn. 1949. pp. 69-83.

9-205 Schoen, Z. John, and Dimmick, Forrest L., Relative Efficiency of Goggles for Dark Adaptation. Report No. 150. Progress Report No. 1 on BuMed Research Project NM 003-014 (S-757(Av-387-k)). Medical Research Lab., U. S. Naval Submarine Base, New London, Conn. April 9, 1949.

9-206 Shilling, C. W., Binoculars with Treated Surfaces. Medical Research Lab., U. S. Naval Submarine Base, New London, Conn. August 21, 1942.

9-207 Shilling, C. W., Report on a Comparison of a Rigid Binocular with the Standard Adjustable Binocular and on Interpupillary Distance Setting Gauge. U. S. Office of Scientific Research and Development, National Defense Research Committee, Appl Psychol Panel. July 23, 1943.

9-208 Smith, T., Report on an Experimental Investigation to Determine the Influence of Veiling Glare on Vision through Telescopes in Daylight. Great Britain. Dept. of Scientific and Industrial Research, National Physical Lab. OSRD Liaison Office, Ref. No. WA-4008-6, NPL/Misc/73. February 13, 1942.

9-209 Sperling, Harry G., and Farnsworth, Dean, Periscope Acuity at Night: Central and Paracentral Acuity as a Function of Contrast and Adaptation. Report No. 157. Vol. 9. 1950. pp. 128-149. BuMed Project NM 003 041.39.01. November 28, 1950. Medical Research Lab. U. S. Naval Submarine Base, New London, Conn.

9-210 Stair, Ralph, Spectral-Transmissive Properties and Use of Eye Protective Glasses. Circular 471. National Bureau of Standards. October 8, 1948.

9-211 Stieglitz, W. L., Cockpit Design and Safety. The Daniel and Florence Guggenheim Aviation Safety Center at Cornell University, New York. (Republic Aviation Corporation), Presented at Annual Summer Meeting of Institute of Aeronautical Sciences at Los Angeles, Calif. July 1952.

9-212 Strughold, H., Investigations on the Usefulness of Contact Lenses in Flight. I. The Sensibility of Cornea and Conjunctiva of the Human Eye. Project 21-24-008. Report 1. USAF School of Aviation Medicine, Randolph Field, Texas. May 1951.

9-213 Strughold, H., The Human Time Factor in Flight. I. The Latent Period of Optical Perception and Its Significance in High-Speed Flying. Unnumbered Project. USAF School of Aviation Medicine, Randolph Field, Texas. January 1951.

9-214 Verplanck, W. S., Determination of Sky Brightness. A. Table of Sky Brightness Measurements. Report No. 44. Medical Research Lab., U. S. Naval Submarine Base, New London, Conn. August 9, 1944.

9-215 Verplanck, W. S., A Field Test of the Use of Filters in Penetrating Haze. Report No. 113. First and Final Report on BuMed and Surg. Research Project NM-011-033 (formerly X-638 (Av-330-p) and BuOrd Project C-3513). Medical Research Lab., U. S. Naval Submarine Base, New London, Conn. June 6, 1947.

9-216 Vinache, W. E., "Illusions Experienced by Aircraft Pilots While Flying." J. Aviat. Med. Vol. 18. 1947. pp. 308-325.

9-217 Wald, George. Factors Which Govern the Change in Focus Required by Optical Instruments When Used at Low and High Illuminations. Monthly Progress Reports I and 2. U. S. Office of Scientific Research and Development. Committee on Medical Research. July 31, 1945 and October 1, 1945.

9-218 Weinbach, A. P., and Lee. R. H., Report on the Influence of Brightness of Red and White Preadapting Lights on the Course of Dark Adaptation for Various Colors of Test Fields and Tests of Specific Goggles Submitted by the Medical Research Section, Bureau of Aeronautics. Report No. 45. U. S. National Research Council, Committee on Aviation Medicine. March 25, 1942.

9-219 West, [illegible], Jones, [illegible] W., [illegible], [illegible] R., [illegible], Mrs. M. W., and Cannon, William H., State of the Earth's Atmosphere in the Arctic. Research Report No. 2. University of Alaska, Geophysical Observatory. Watson Labs., AMC, Red Bank, N. J. November 17, 1948.

9-220 Westheimer, Gerald, "The Design and Ophthalmic Properties of Binocular Magnification Devices." Amer. J. Optom. and Arch. Amer. Acad. Optom. Vol. 31. No. 11. November 1954.

9-221 Whiteside, T. C. D., Vision at High Altitude. Great Britain. Flying Personnel Research Committee, Royal Air Force Institute of Aviation Medicine. 1954.

9-222 Whiteside, T. C. D., and Bazarnik, K., The Dazzle Effect of an Atomic Explosion at Night. Great Britain. Flying Personnel Research Committee. Report No. 787, OANAR S No. 4746. May 1952.

9-223 Wilson, Clark L., Some Psychological Problems in the Use of Periscope Type Instruments. USAF Tech. Report 5833. Wright-Patterson Air Force Base, Ohio. February 1950. (CONFIDENTIAL)

9-224 Wright, Fred E., The Effect of Curved Windshield Glass on Transmitted Rays of Light. U. S. National Academy of Sciences. June 1940.

9-225 Wynne, C. G., Primary Aberrations of Anamorphotic Lens Systems. 1954.

CHAPTER 10

AIR-TO-AIR VISIBILITY

Air-to-air visibility means the visibility of one aircraft from another, or of any objects in the sky from an aircraft. The term covers both detection and identification. Problems of air-to-air visibility tend to be the same for all types of mission, and somewhat different from problems of air-to-ground visibility for all types of mission. For example, the visual functions, the effects of atmosphere, and the effectiveness of visual aids are about the same for an airways pilot seeking to avoid collision as for a combat pilot seeking out enemy aircraft except for differences in range and visual field requirements. On the other hand, the problems of air-to-ground vision tend to be similar, whether the pilot is looking for enemy installations in a bombing or reconnaissance mission or seeking to identify objects for navigational purposes. That is why we have grouped air-to-air problems in this chapter, and air-to-ground problems in another chapter. Some of the air-to-air problems covered in this chapter are as follows: Visibility and the avoidance of collision, visibility in interception, and formation flying. In addition, such matters as scan patterns, prediction of target visibility, and ways of making aircraft easier to detect are discussed.

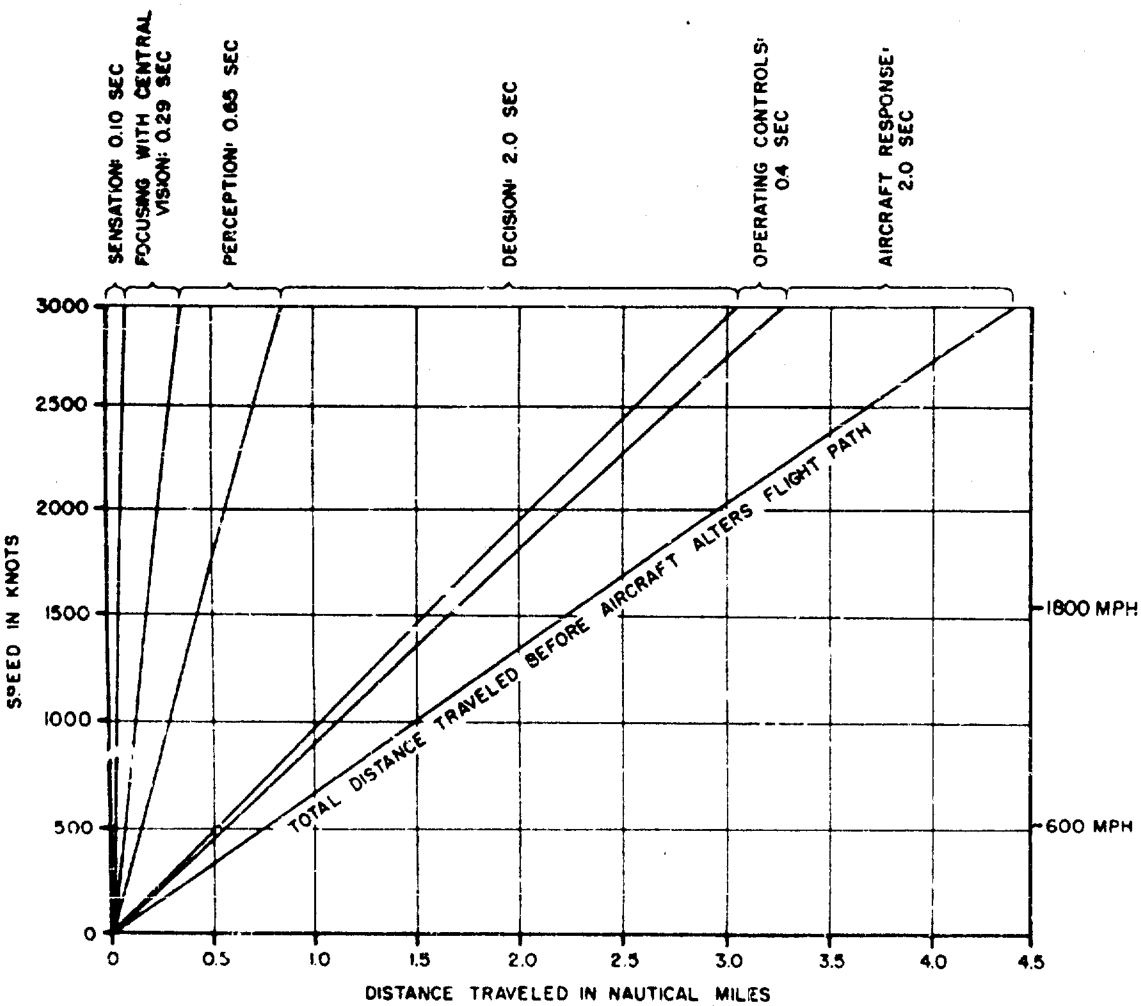


Figure 10.1 Minimum Distances Traveled From Instant Object Comes Into Field of Vision Until Pilot Can Change Flight Path

VISUAL PROBLEMS DUE TO SPEED

High speeds, altitudes, and accelerations, work load, airport density, complicated instrument panels, and the structure of the aircraft itself all create serious visual problems for the pilot and crew of high-performance aircraft. The most critical of these is high speed. At the speeds flown by today's jet aircraft, a perfectly ordinary situation, such as sighting an object a mile away, can turn into a calamity before the pilot can do anything about it. As speeds get higher, the problem will become worse in proportion. The trouble is simply that a man cannot see, identify, or act on an object the instant it comes into his field of view. Each of these things takes an interval of time -- usually an exceedingly short interval, but worth hundreds or thousands of feet in a high-speed aircraft.

This point is brought out in Table 10.1. Consider a pilot flying at 600 miles an hour, a routine speed for jet aircraft at this writing. Another aircraft comes into his extra foveal vision -- the corner of his eye. He travels 88 feet before he even "sees" it -- before the image is transmitted

Table 10.1 Time Intervals Required Between First Sighting of Object and Changing Flight Path to Avoid and Distances Traveled in These Intervals*

Operation	Time, in sec: For Operation	Time, in sec: From 1st Sighting	Distance Traveled, in feet, at 600 mph: During Operation	at 600 mph: From 1st Sighting	at 1800 mph: During Operation	at 1800 mph: From 1st Sighting
Sensation (light travels from retina to brain)	0.10	0.10	88	88	264	264
Focusing with Central Vision						
Motor Reaction to Prearrange Eye Movement	0.175	0.275	154	242	462	726
Eye Movement	0.05	0.325	44	286	132	858
Focusing with Fovea	0.07	0.395	62	348	185	1043
Perception (minimum recognition)	0.65	1.045	572	920	1716	2759
Deciding What to Do (estimated min.)	2.0	3.045	1760	2680	5280	8039
Operating Controls	0.40	3.445	352	3032	1056	9095
Aircraft Changes Flight Path	2.0	5.445	1760	4792	5280	14,375

*Derived from Moseley[10-11] and Byrnes[10-6]

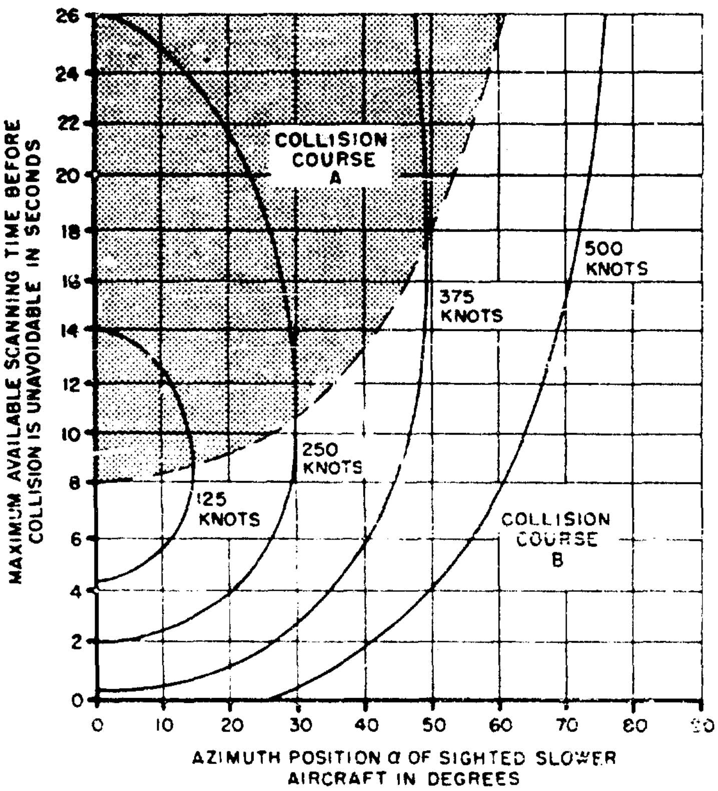
from retina to brain. He travels 920 feet before he has "perceived," or recognized it -- before he has decided, for example, whether it is a cloud or another aircraft. He travels more than half a mile before he has decided whether to climb, descend, or bank to right or left. He travels nearly a mile before he can actually change his flight path to avoid or attack. At 1800 miles an hour, already achieved in piloted rocket aircraft, these distances are trebled; the pilot travels a mile and a half before he can even decide what to do, and nearly three miles before he alters his flight path. Distances for aircraft flying at other speeds may be obtained from Figure 10.1.

For two aircraft on opposite courses, the distances they travel relative to each other would be double those in Table 10.1 and Figure 10.1. Suppose two aircraft came out of the clouds heading for each other at 1800 miles an hour. If they emerged 500 feet apart, they would crash before either pilot

had even seen the other aircraft. If they emerged three miles apart, they would crash before the pilots had decided what maneuver to take, and, if they emerged five miles apart, they would still be too close to change their flight paths. Even at 600 miles an hour, the pilots would have to see each other 9500 feet away, at the very minimum, before they could change their flight paths to avoid collision.

Some of the time intervals in Table 10.1 are not subject to careful measurement, and the values given are estimated. However, if they err, it is probably on the side of being too small. Moreover, it has been assumed that conditions are ideal (clear day; alert, experienced pilot; no distractions) and that only the simplest kinds of operations are involved. In short, the time intervals in Table 10.1 are probably absolute minima. They cannot be reduced by any amount of mechanical or electronic ingenuity, because (except for the last item, which involves aircraft response) they are due solely to unchanging characteristics of the human eye, mind, and muscle. Likewise, the distance traveled in each interval will increase directly and inexorably as speed increases, because no human can alter the fact that distance = speed x time.

The time intervals and distances in Table 10.1 could be extended several seconds and thousands of feet by any number of complications that occur in perfectly normal flight. For example, anything that interfered with the pilot's vision, whether it were a structural member of the aircraft, encumbrance of flight clothing, haze, or gray-out induced by high acceleration, could greatly stretch the time required to perceive and recognize. If the pilot had not only to identify the object as an aircraft, but also to decide whether it were an enemy or a friendly plane, the recognition time would probably



ASSUMPTIONS:
SIGHTING DISTANCE = 2-1/2 NAUTICAL MILES
PILOT'S DECISION TIME = 2 SEC
AIRCRAFT REACTION TIME = 8 SEC
SPEED OF FASTER AIRCRAFT = 500 KNOTS
SPEED OF SLOWER AIRCRAFT = (LABELED ON CURVE)
PLANES ARE ON A COLLISION COURSE

Figure 10.2 Maximum Available Scanning Time Under Various Conditions

stretch out to at least 1.5 seconds (1320 feet at 600 mph). Decision time is probably four or five seconds, rather than the two given in the table, for any but the most experienced pilots and the most simple decisions.

Figure 10.2 illustrates the critically short scanning time available to pilots of high-speed aircraft in collision courses. Note that there are normally two values of scanning time, corresponding to the two possible collision courses A and B. Condition A represents the case of two aircraft flying convergent courses. Condition B represents the case of two aircraft approaching from a more or less headon aspect. The area above the dashed line applies to the more favorable case. For example, if α is 25° and the slow aircraft is flying at a speed of 250 knots, the pilot has 15.3 seconds of scanning time on Course A or 5.5 seconds on Course B.

At high speeds, a pilot flies "blind" for thousands of feet while performing such a simple operation as glancing at an instrument. Table 10.2 shows that at 600 miles an hour, his vision outside the aircraft is interrupted over nearly half a mile. At 1800 miles an hour, it is interrupted over more than a mile. Again, if two approaching aircraft were involved, distances would be doubled. If a pilot flying at 600 miles an hour glanced at his altimeter, an enemy aircraft coming out of the clouds a mile away could be on him before he knew the enemy was there. The same type of information for aircraft at other speeds can be obtained from Figure 10.3.

Table 10.2 Time Intervals Required to Shift Sight From Outside Aircraft to Instrument Panel and Back, and Distances Traveled in These Intervals

Operation	Time, in sec.		Distance Traveled, in feet			
			at 600 mph		at 1800 mph	
	For Operation	From Beginning	For Operation	From Beginning	For Operation	From Beginning
To Panel						
Muscle Movement	0.175	0.175	154	154	462	462
Eye Movement	0.05	0.225	44	198	132	594
Foveal Perception	0.07	0.295	62	260	185	779
Accommodation	0.50	0.795	440	700	1320	2099
Recognition of Instrument Reading	0.80	1.595	704	1404	2112	4211
Back to Distance						
Reaction Time	0.175	1.770	154	1558	462	4673
Eye Movement	0.05	1.820	44	1602	132	4805
Relaxation of Accommodation	0.50	2.320	440	2042	1320	6125
Foveal Perception	0.07	2.39	62	2104	185	6310

In shifting sight from outside the aircraft to the instrument panel and back, the accommodation time -- the time to adjust the eyes to focus on the instrument -- becomes important. Table 10.2 shows that accommodation and relaxation of accommodation takes up a total of a second, or half a mile at 1800 miles an hour. Recognition -- ascertaining what the instrument reads -- will consume a great deal more time than 0.80 seconds if the instrument is poorly lighted or designed. Likewise, if the sky were bright and the panel were dimly lighted, the pilot would first have to adapt his eyes to the dim light within and then readapt to the brightness outside. A dangerously long time interval would be used up. It is not surprising, therefore, that good cockpit lighting and well-designed and standardly located instruments are of concern to all who fly high-speed aircraft. It is also obvious

that the day is rapidly approaching when a pilot will no longer have time to make navigational calculations on his knee pad. An instrument showing aircraft position at a glance will be as necessary as a compass is now.

The foregoing discussion applies both to the problems of avoiding collision and intercepting or avoiding enemy aircraft. Let us pursue these matters further.

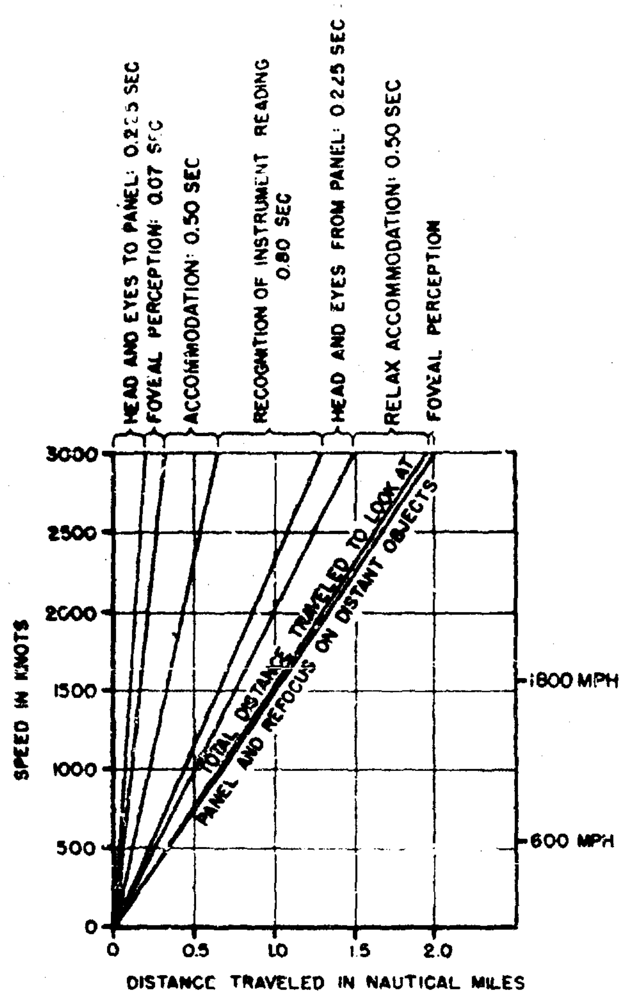


Figure 10.3 Minimum Distance Traveled While Pilot Shifts Sight to Instrument and Back

AVOIDING COLLISION

Because the problem of mid-air collisions had become so critical, the CAA sponsored a mid-air collision symposium in late 1955[10-1]. There were many speakers representing all phases of the aviation industry. They brought out the following points:

The Air Force, over one 2-1/2-year period, had about 150 mid-air collisions. Of these, about 92 per cent could be attributed to failure of the pilot to see the other aircraft in time to avoid collision. In some cases, the pilot never saw the other aircraft at all. When the other aircraft could be seen, contributing factors were misjudgment of distance and rate of closure and the possibility that both pilots, in attempting to turn off, turned into each other. Also interesting was the fact that 70 percent of these collisions occurred while the aircraft were in straight and level flight. The Navy, too, presented data from 23 mid-air collisions occurring over a two-year period. The majority of these accidents took place during daylight hours and occurred in flight rather than during take-off or landing. CAA data[10-2] for civilian flying, covering the years 1953 and 1954, show two mid-air collisions for the scheduled airlines and 25 for nonscheduled carriers.

In addition to actual mid-air collisions, many near misses are reported. The near misses of today could easily be collisions in the future, when there are more aircraft and all are traveling faster. The Air Transport Association of America sent a questionnaire to airline pilots to find out how and where their near misses occurred. As with the Air Force collisions, the majority of near misses occurred en route, and most occurred during full daylight when visibility was reported to be 15 miles or more. A dangerous condition exists when one aircraft is flying IFR (instrument flight rules, with ground control centers maintaining separation between aircraft) and the other is flying VFR (visual flight rules, with the pilot mainly responsible for avoiding collision).

Two general conclusions can be drawn from the mid-air collision symposium. First, there is a pressing need to learn more about the limits of visual detection and the reasons these limits exist, so that demands will not be placed on pilot and crew that exceed their visual capacities. Second, improved ground-control techniques and airborne detection equipment should be developed to relieve the pilot of some of the burden of continuous vigilance for other aircraft.

INTERCEPTION

In interception with fixed gunnery, a pilot actually tries to get on something approaching a collision course with another aircraft. If efficient flexible gunnery or homing missiles are developed, a collision course will not be necessary. Interception includes identifying unreported aircraft, attacking enemy aircraft, and rendezvousing with friendly aircraft for refueling or formation flight. Usually electronic equipment, either on the ground or airborne or both, helps the pilot perform his interception problem. Nevertheless it is usually desirable and often necessary that a pilot see the aircraft he is intercepting as early as possible. It can be seen that the problems of interception are much like those of avoiding collision, but there are some differences. The most important are: (1) In interception, it is often important to see another aircraft at a great distance, so that the intercepting aircraft can maneuver into an attacking position. In avoiding collision, it is important only that the other aircraft be seen in time to avoid collision. (2) In interception, it is often necessary to identify another aircraft positively. In avoiding collision, identification is not important, though the other aircraft must be seen well enough so that its course can be estimated. (3) In combat interception, the problem is often to detect and identify an aircraft that is painted so as to be as inconspicuous as possible, or that is blacked out at night. Where the central problem is preventing collisions, paints, markings, and lights can be designed to make all aircraft as conspicuous as possible. (However, when combat aircraft are painted and lighted for maximum concealment from the enemy, they have an added problem of avoiding collision with each other.)

FORMATION FLYING

Good air-to-air visibility is also required in formation flying. During daylight, other aircraft can usually be seen well enough to fly formation; the chief problem is to station each aircraft so that it does not obstruct too much of the fields of view of the other pilots. For example, if a tight formation is flown, it is difficult to cover each other for the position of the sun. At night, however, light must be provided (except in combat) so that the wing man can match the attitude of his aircraft to that of the lead aircraft. As we shall see later in this section, standard navigation lights have been found to be unsatisfactory for formation flights.

One study[10-7] has indicated that, in general, detection is most difficult against a terrain background, easiest against an undercast, and medium difficult against a sky background. These differences are due to the characteristics of the observer as well as the physical situation.

In the remainder of this section, we will take up separately the characteristics of the observer and the physical factors that affect air-to-air visibility, methods of predicting visibility, and methods of avoiding detection.

CONTRAST DISCRIMINATION

Detecting aircraft against various backgrounds is much like taking a laboratory test to measure minimum perceptible acuity (see Chapter 8). This type of visual performance was found to depend on (1) the over-all level of illumination, (2) how well the observer is adapted to the over-all illumination, (3) the contrast between the target and the background, (4) the apparent size of the target -- that is, the visual angle subtended by the target, and (5) movement in relation to the background.

The relationship between these variables is shown in the contrast discrimination curves, Figures 8.12 and 10.4. These curves show that the ability to detect differences in the brightness of objects increases as illumination increases. In other words, less contrast is required to detect a target against a fairly bright background, such as an undercast, than against a dark background, such as the ground.

The curve in Figure 8.12 (Chapter 8) emphasizes the importance of the target's apparent size (i.e., the visual angle subtended) in determining whether the target will be seen. This curve shows that if the brightness of the sky or other background and the inherent contrast between aircraft and background remain constant, there will be a threshold size below which the aircraft cannot be seen. As an aircraft approaches an observer, the visual angle which it subtends increases; when its apparent size equals the threshold size, it can be seen.

Note that contrast discrimination and visual acuity depend not only on the physical characteristics of the target but also differ with different individuals and for one individual at different times.

Contrast discrimination and minimum perceptible acuity are of chief importance when one is estimating the range at which an aircraft can be detected.

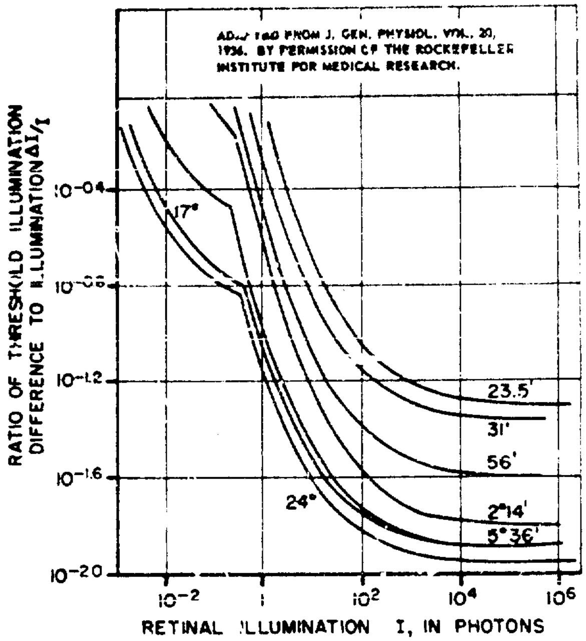


Figure 10.4 Contrast Discrimination in the Human Eye as Influenced by Retinal Illumination and Size of Test Field (from Steinhardt[10-14])

SIZE OF THE USEFUL VISUAL FIELD

Another characteristic related to detection is the size of the visual field in which the target must fall in order to be detected. Where the problem here is detecting a small object, such as an aircraft, at maximum distance, foveal vision is required. That is, in order to be detected at any distance, the target will have to pass through a small cone less than one degree in cross-section, containing the pilot's or observer's visual axis, and with its apex at his fovea. This can be seen from Figure 10.5, which shows visual acuity as a function of retinal position. The size threshold increases as the target moves away from the fovea. However, if the target is close enough or large enough to subtend more than the threshold angle for central vision, it can be detected some distance into the periphery. One investigator[10-9] shows that a target twice the threshold size for central vision can be detected over 10-degree cone, while a target four times threshold size can be detected anywhere in a 26-degree cone.

SCANNING PATTERNS

The size of the cone in which targets can be detected is important because of the expanse of sky that must be searched to detect aircraft approaching from any direction. An observer has no accurate, subjective means of knowing whether his scanning pattern is fine enough -- whether he is covering all areas of the sky by the cone within which he can detect the target. To make matters worse, the sky is generally empty of visual references that could serve as guides for a systematic scanning pattern. Even after a target has been detected, it becomes difficult to locate again if the eyes are shifted from it momentarily, because there are no visual references. The boundaries and structure of the windshield provide a little aid as a visual reference.

With the coming of high-performance aircraft, pilots have had difficulty locating each other when attempting to rendezvous at prearranged positions at high altitudes. At first it was thought that this failure was due to navigational error at high altitudes. It has become clear, however, that there is a more direct and fundamental reason. It has been related that fighters have chased

enemy aircraft for over 100 miles, knowing from their electronic aids that they were always as close as five miles and sometimes less than one mile away, but never once sighting them visually. Over 90 percent of the sightings made by fighters above 40,000 feet were by means of glints of light flashing from the aircraft being detected. Such glints occur only when the aircraft maneuvers so that the specular reflection from its surfaces happens to be directed toward the observer. In other words, if it does not glint, it probably will not be detected.

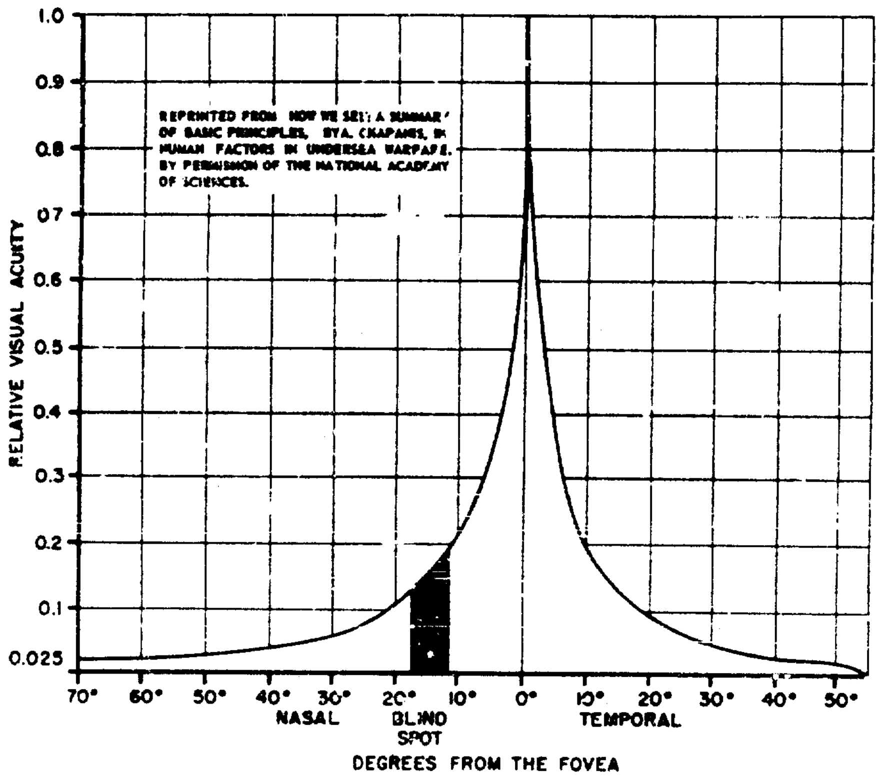


Figure 10.5 Curve of Daylight Visual Acuity for Different Parts of the Eye (see Wertheim[10-16])

One explanation for such failures to detect at altitude is that the pilot, having nothing to look at, at a distance, unconsciously keeps his eyes in focus for objects near at hand. He is suffering from a kind of near-sightedness called empty-field myopia. He does not see distinctly small objects at a distance.

The eye seems to accommodate to a state between 0.2 and 0.9 diopters when viewing an empty field such as the sky. Convergence is also adjusted for something less than infinity.*

A laboratory experiment[10-9] indicated that empty-field myopia may reduce the aircraft detection range to half what it would be if the eye were accommodated for infinity. The experimenter suggests that it would be worthwhile to correct empty-field myopia by the use of negative spectacles. He says that for a person with normal vision, such spectacles would raise his accuracy of detection to the level of a far-sighted observer. However, it is probable that the eye would merely accommodate more to offset the effects of the glasses.

As an alternative, it has been suggested that observers could learn to relax the eyes so as to accommodate voluntarily for distance. However, one investigator[10-17] states that involuntary accommodation for less than infinity cannot be overcome by training. Instead, he favors placing a reticle pattern of concentric rings at optical infinity -- that is, so that the pilot must focus at infinity for the rings to form an intelligible image. He found, however, that the visual angle subtended by the rings must be small to be effective. Furthermore, any reference point more than 5 degrees from the line of sight will be ineffective in overcoming empty-field myopia. This means that when scanning is required, the reticle would have to move with the eyes. A device for accomplishing this might easily turn out to be cumbersome and impractical. The role of convergence in space myopia may be considerable and seems to merit further attention and study.

PROPERTIES OF THE ATMOSPHERE

In Chapter 9 we reviewed recent research on the optical effects of meteorological conditions and time of day. Here we will consider the practical effects of atmosphere on visibility.**

At high altitudes, a brilliant sun against a dark sky often interferes with vision. Reflections from one's own aircraft and an undercast of clouds make the situation worse. As one ascends, the sky becomes darker until at very high altitudes it becomes very dark. This is due to the thinning of the atmosphere and the consequent reduction in scatter of light. At the same time the sun becomes about 30 percent brighter because there is less atmosphere to filter and absorb its light. The sun thus becomes a very bright light in a black sky. The only source of diffuse, extended illumination is below rather than above -- an effect accentuated by an undercast of clouds. This situation presents several difficulties for the pilot who must search for other aircraft. First, the human eye cannot comfortably adapt to brightnesses beyond a certain level. The bright sun and clouds viewed at altitude are certainly approaching this level. Discomfort is often reported by pilots. One result is that they spend less time searching the skies for other aircraft than they would ordinarily. Second, the high contrast between sun and sky makes objects in the sky still harder to detect. Third, glare is caused by reflections from the bright parts of the pilot's or observer's own aircraft and from clouds below.

When situations are favorable for glare due to a bright sun or reflections or both, a target may be behind a region of bright illumination -- a veiling luminance, it is called. The eye must penetrate this luminance to see the target.

Since the predominant direction of illumination is from below, the cockpit is often very dark compared to the bright sky. The pilot must adapt to the low brightness of the cockpit before he can read instruments, charts, etc. This situation can be corrected by proper cockpit lighting, as discussed in Chapter 13.

CHARACTERISTICS OF THE TARGET

The reflectivity*** of an aircraft determines how bright it will appear under a given amount of illumination. For aluminum aircraft, reflectivity varies from very low values up to as much

---

* It will be remembered from Chapter 4 that when an eye is focused for infinity, it is also focused for anything 20 feet or farther away. When the visual axes of the two eyes are parallel -- converging at infinity -- there is little appreciable double image beyond about 50 feet.

** Much of the material here and in the discussion of target characteristics immediately following has been drawn from a review article.[10-9]

***Reflectivity is the ratio of light reflected to light falling on a surface.

as 80 percent. The contrast with the sky background is often low and variable; it depends on the relative positions of the sun, observer, target aircraft, and the location of clouds, etc. During varying conditions of flight, the contrast of a particular aircraft may change back and forth between low negative and positive contrast values; that is, it may change from slightly less bright to slightly brighter than the sky and vice versa. As it passes through zero contrast, the only basis for detection would be texture or color except that these are of almost no value at the distances involved. However, an aircraft cannot be detected at anywhere near as great a distance on the basis of these as on the basis of an adequate brightness contrast.

Another characteristic of the target thought to influence its detectability is relative motion. It is known that acuity judgments are poorer when a target is moving than when it is stationary.[10-10] Various explanations have been offered for this fact. One is that the eye does not track moving target smoothly. However, the tests of the effect of motion were made for minimum separable acuity* rather than minimum perceptible acuity; the latter seems to be the type of visual acuity that is important in detection. Whether or not the motion itself makes an aircraft less visible, it may make it more attentionable, except that the higher the speed of the aircraft, the less time it will be within detection range. Thus, when large areas must be scanned, the probability of detection will usually be less for high-speed aircraft than for slower ones.

Ordinarily, detection of a target is probably made easier by its motion across a varied background or in respect to stationary objects in back of it. When one is at high altitude, however, the background of other aircraft at high altitude is usually an empty and unvarying sky, with no stationary reference objects; motion relative to it is not easily detected. Relative movement is therefore not apparent, and this may be another reason why aircraft are more difficult to detect at high altitudes than at low.[10-7]

PREDICTION OF TARGET VISIBILITY

A method for predicting target visibility under a wide variety of atmospheric and target conditions would be very useful. As explained in Chapter 9, many workers are trying to discover what governs visibility and to collect the data required to establish the constants for atmospheric attenuation equations. The techniques for prediction that have been developed are of uncertain value, for few field tests have been made to try them out. However, one study[10-1] sheds some light on the matter. In this study, two groups of airline pilots, flying cross-country, reported when they first detected aircraft approaching on collision courses. One group was deliberately misinformed. It was told that the study was concerned with eye movements made with two types of instrument displays. However, these pilots were also told that if they should see another aircraft in the vicinity they should report it to the safety pilot. During their flights, another aircraft was put on one of four different collision courses with their aircraft. The second group of pilots, the "informed group," was told they were on a collision course with another aircraft, but they were not told from what direction it was approaching. An engineer who knew where to look also recorded where the collision aircraft was first detected. The results are shown in Table 10.3.

Table 10.3 Distance at Which Aircraft on Collision Course was Detected

Relative Bearing to Collision A/C	Detection Distance		
	Engineer Knew Where to Look	Pilots Informed	Pilots Misinformed
0° (head-on)	11 miles	5.00 miles	3.50 miles
30° left	14	4.50	5.00
60° left	12	4.50	4.50
100° left	10-1/2	4.75	3.50

*For the various types of visual acuity, see Chapter 8.

The conditions for these tests were not described completely in the report; it was stated simply that CAVU weather conditions existed (i.e., ceiling and visibility unlimited). Therefore an exact comparison of predicted visibilities cannot be made. However, the range of detection reported by the engineer is of the same order of magnitude as would be obtained from appropriate visibility nomographs.[10-8]

The most striking point brought out by Table 10.3 is that while the targets could be detected at 10 to 12 miles, the pilots, both the informed and the misinformed, failed to pick them up until they were 3 to 5 miles away -- until they were at about one third the detectable range. This discrepancy is probably due to the time required to scan large areas of the sky; the aircraft came in one sector while the pilot searched others. Some visibility prediction equations take this factor into account; the result is a statement of probability about the range at which an aircraft will be detected. Computations by one worker[10-4] are an example of this kind of visibility prediction. He notes that high-speed interceptors can sometimes open fire on bombers before they are detected. He has computed the probabilities of a bomber crew's detecting an attacking high-speed interceptor at various ranges, assuming certain operating conditions. For example, when the planes are closing at a relative speed of 1000 knots, the interceptor will be detected beyond one nautical mile only 64 percent of the time and before two nautical miles only 26 percent of the time. He concludes that visual detection should not be relied upon for the detection of high-performance interceptors. This report includes the parameters and mathematical development required for computing detection probabilities when scanning with the eyes. Such computations are also useful for determining the probability that a fast fighter aircraft will lose visual contact with a bomber while breaking off its attack and circling to attack again.

MAKING AIRCRAFT EASIER TO DETECT

By Day

Under some conditions it is desirable to make aircraft as easy to detect as possible. One would think that the best way would be to paint the plane so as to increase its contrast with the background. However, since the contrast seems to range from low negative values to low positive ones, depending on sky brightness, neither making the plane darker nor lighter will help under all conditions. Two investigators[10-15] experimented with numerous patterns of paint on model airplanes viewed under a wide variety of simulated sky conditions. The pattern that improved visibility most was a glossy sea blue paint applied to the trailing halves of the tail and wing surfaces, with the leading halves left as bare aluminum; when the sky was bright, the dark, painted areas provided good contrast with the sky, and when the sky was dark the aluminum areas provided good contrast. The authors feel that the best patterns they studied should be tested on aircraft under actual conditions.

By Night

Many pilots find the standard night lighting system on aircraft unsatisfactory for formation flights. Under the standard lighting system the attitude of adjacent aircraft must be judged from two or three points of light; the silhouette cannot be seen because of the lights. Therefore, many pilots prefer to fly formation with the lights of the other aircraft turned off. When this is done, they can see a dim silhouette against the night sky that gives them a basis for judgment attitude. One worker[10-12] studied a variety of lighting combinations in actual flight tests. He concluded that several lights should be added. These include (1) section lights on top and bottom of the fuselage just behind the cockpit and (2) formation lights consisting of illuminated panels, set in the underside of the wing. In general, flashing lights were found useful for rendezvousing but impossible for formation flying. It was also recommended that each aircraft be equipped with a three-position switch which would adjust the intensity of the lights; an extremely faint position would be provided for formation flight.

Another lighting system tried was floodlighting the wings and tail surfaces of the lead aircraft. While this system provides excellent reference for formation flight, it is not very practical. However, the investigator[10-13] suggests that some aircraft might be equipped with floodlights for training in formation flying. Other lighting systems that might be tried are illuminated lucite caps for the wing tips and lucite rods to mark the major axes of the lead aircraft.[10-12]

Another worker[10-3] also recommends that provision be made for dimming aircraft lights for formation flying. He has tabulated recommended candle powers for each aircraft light and advises whether each light should be on, off, or flashing in cruise, join-up, and formation flight. He further recommends a redesigned top light. Research on night lighting and night formation flight is reviewed in references 10-3 and 10-5. The latter summarizes most of the research conducted by the Navy in this field.

LIST OF REFERENCES

10-1 Anon. Report of Presentations and Discussions at the Mid-Air Collision Symposium. Civil Aeronautics Administration. Indianapolis, Ind. 1955.

10-2 Anon. Statistical Handbook of Civil Aviation. Civil Aeronautics Administration. U. S. Government Printing Office, Washington, D. C. 1955.

10-3 Baker, C. A., Formation Lights for Fighter Aircraft. WADC Tech. Report 55-124. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. March 1955.

10-4 Bieber, V. E., Report No. DR-1466. Bureau of Aeronautics, Navy Department, Washington, D. C. 1953. (CONFIDENTIAL)

10-5 Blasdel, I. C., and Lazo, J., Study of Exterior Lighting for Navy Airplanes, Part 6. Report TED NAM 31333. U. S. Naval Air Experimental Station, Naval Air Materiel Center, Philadelphia, Pa. June 1, 1949.

10-6 Byrnes, V. A., "Visual Problems of Supersonic Speeds." J. Opt. Soc. Amer. Vol. 34. 1951. pp. 169-177.

10-7 Emerson, G. O., Minutes and Proceedings Armed Forces NRC Vision Committee. 1952.

10-8 Festinger, L., Kelly, H. H., Orlansky, J., and Coakley, J. D., Estimates of Visibility from High-Altitude Aircraft. Prepared by The Psychological Corporation for the Office of Naval Research, Special Devices Center, Port Washington, N. Y. 1948. (CONFIDENTIAL)

10-9 Koomen, M. J., Comments on Air-to-Air Visibility at High Altitude. Micron Waves Branch, Optics Div., Naval Research Laboratory, Washington, D. C. 1954.

10-10 Ludvigh, E. J., Visual and Stereoscopic Acuity for Moving Objects. Symposium on Physiological Psychology. Office of Naval Research. 1955.

10-11 Moseley, H. G., "The Challenge of High-Speed Flying." The Atlantic. July 1956. pp. 62-64.

10-12 Orlansky, J., Study of Exterior Lighting for Navy Airplanes: III. Flight Tests of Some Exterior Lighting Systems to Facilitate Rendezvous and Formation Flying of Naval Aircraft a[illegible]ght. Report TED NAM 31333. U. S. Naval Air Experimental Station, Naval Air Materiel Center, Philadelphia, Pa. July 1946.

10-13 Orlansky, J., Study of Exterior Lighting for Navy Airplanes. Report No. 2 on the Use of Floodlights for Exterior Lighting of Naval Aircraft. Report TED NAM 31333. U. S. Naval Air Experimental Station, Naval Air Materiel Center, Philadelphia, Pa. June 1946.

10-14 Steinhardt, J., "Intensity Discrimination in the Human Eye. I. The Relation of ΔI/I to Intensity." J. Gen. Physiol. Vol. 20. 1936. pp. 18[illegible]-209.

10-15 Wagner, H. C., and Blasdel, I. C., Visibility Studies of Exterior Color Schemes for Aircraft vs. Present Aluminum Color. Report TED NAM AE-520044. U. S. Naval Air Experimental Station, Naval Air Materiel Center, Philadelphia, Pa. 1948.

10-16 Wertheim, T., "Uber die Underekts Sehscharfe." Z. Psychol. Vol. 7. 1894. pp. 172-187.

10-17 Whiteside, T. C. D., Vision in an Empty Visual Field. The Relation of the Effectiveness of a Stimulus at the Far Point to its Angular Distance from the Fovea. Report No. 898. Great Britain. Flying Personnel Research Committee, Royal Air Force Institute of Aviation Medicine. 1954.

10-18 Anon. U. S. Navy, Office of Chief of Naval Operations. Operations Evaluation Group Study No. 430, Addendum to OEG Study No. 388. November 21 1950 (CONFIDENTIAL)

10-19 Anon. The Cornell Committee for Air-Safety Research. Cornell University, Cornell Medical College and Cornell Aeronautical Laboratory, Inc. 1950.

10-20 Anon. Crew Errors in B-29, B-50, B-36, B-45, B-47 Major Accidents. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. Vol. 1. June 30, 1952. pp. 1-50.

10-21 Anon. Report No. 309. Operational Research Section. Great Britain. Royal Air Force Coastal Command. October 7, 1944. (SECRET)

10-22 Anon. Investigation of Visibility of Exterior Aircraft Lights. U. S. Naval Air Test Center. March 1953.

10-23 Anon. Military Characteristics of a Visual and Infrared Omnidirectional Blinker for Ships. U. S. Navy, Bureau of Ships. (University of Michigan)

10-24 Anon. Night Observations from the Air. Great Britain. Air Ministry Pamphlet [illegible] June [illegible]

10-25 Anon. Night Vision Testing with the Rotating Hexagon. Also: Effect on Night Visual Acuity of Blue-Green and Red Filters in Reflex Gunsights. U. S. Army-Air Forces, Hq., Office of the Air Surgeon, Research Div., Psychological Branch. May 4, 1944.

10-26 Anon. "References on the Uses of Modern Light Polarizers." Polaroid. January 1952.

10-27 Anon. Survey of Research Reports in the Field of Aviation Safety. Guggenheim Aviation Safety Center at Cornell University. January 1953.

10-28 Anon. A Symposium: Psychophysiological Factors in Spatial Orientation. U. S. Navy, Office of Naval Research. October 30-31, 1950.

10-29 Anon. Vision in Starlight and Moonlight (II) Adaptation to Prevailing Brightness. ARL R2/84.05/0 Admiralty Research Laboratory, Teddington, Middlesex, England. January 1944.

10-30 Anon. Visual Detection in Air Interpretation. U. S. Navy, Office of Chief of Naval Operations. Operations Evaluation Group Study No. 368. October 26, 1948. (CONFIDENTIAL)

10-31 Adams, O. S., Chambliss, D. J., and Riopelle, A. J., "Stimulus Area, Stimulus Dispersion, Flash Duration and the Scotopic Threshold." J. Exp. Psychol. Vol. 49. 1955. pp. 428-431.

10-32 Adler, H. E., Brown, J. L., and Herrick, R. M., The Effects of Pupil Size and Flash Duration on Acuity during Dark Adaptation. WADC Tech. Report 54-551. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. November 1954.

10-33 Anastasi, A., "The Estimation of Area." J. Gen. Psychol. Vol. 14. 1936. pp. 201-225.

10-34 Anderson, M. J., and Phillips, C. B., Development of Helicopter Blade Tip Lighting. CAA Tech. Development Report No. 248. Civil Aeronautics Administration. October 1954.

10-35 Armstrong, R. C., Night Gunsights. Aeromedical Laboratory. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. January 25, 1943.

10-36 Asch, S. E., and Witkin, H. A., "Studies in Space Orientation: II. Perception of the Upright with Displaced Visual Fields and with Body Tilted." J. Exp. Psychol. Vol. 38. August 1948. pp. 455-477.

10-37 Asch, S. E., and Witkin, H. A., "Studies in Space Orientation: I. Perception of the Upright with Displaced Visual Fields." J. Exp. Psychol. Vol. 38. June 1948. pp. 325-337.

10-38 Bahrick, H. P., Fitts, P. M., and Rankin, R. E., "Effect of Incentives upon Reactions to Peripheral Stimuli." J. Exp. Psychol. Vol. 44. No. 6. December 1952. pp. 400-406.

10-39 Bahrick, H., Rankin, R. E., and Fitts, P. M., The Effect of Motivation upon Peripheral Performance during the Performance of a Central Psychomotor Task. HRRC, Perceptual and Motor Skills Research Laboratory, Air Training Command, Lackland Air Force Base, San Antonio, Texas. April 1952.

10-40 Baker, C. H., and Ogilvie, J. C., Charts of Air-to-Air Visibility of Aircraft in the Upper Atmosphere. Defense Research Medical Laboratories, Canada. 1954. (SECRET)

10-41 Bartley, S. H., and Miller, J. W., "Some Circumstances Surrounding Apparent Movement in the Line of Regard." J. Psychol. Vol. 38. 1954. pp. 453-456.

10-42 Beck, L. H., A Theoretical Evaluation of an Experimental Visual Stereo-Enhancer for Aerial Use. Optics and Vision Group, University of Michigan Vision Research Laboratory. August 7, 1955.

10-43 Beebe-Center, J. C., Carmichael, L., and Mead, L. C., "Daylight Training of Pilots for Night Flying." Aero. Engng. Rev. Vol. 3. 1944. pp. 1-10.

10-44 Beebe-Center, J. C., and Mead, L. C., Relation of Decrease of Brightness at Nightfall to Decrease of Threshold Brightness Due to Adaptation. Commonwealth Fund Report 5. Tufts Bibliography 27. Office of Naval Research, Special Devices Center. 1942. pp. 31-33.

10-45 Beggs, S. S., and Waldram, J. M., A Method of Estimating Visibility from the Air Near the Ground at Night. Research Laboratory Report 8303. General Electric Company. Wembley, England. 1943.

10-46 Berger, C., "The Problem of Peripheral Visual Acuity." Amer. J. Psychol. Vol. 56. 1943. pp. 603-604.

10-47 Bevan, W., and Zener, K., "Some Influences of Past Experience upon the Perceptual Thresholds of Visual Form." Amer. J. Psychol. Vol. 65. July 1952. pp. 434-442.

10-48 Blackwell, H. R., The Inter-Relations of Contrast, Area, and Adaptation Brightness in Human Binocular Vision. PhD dissertation. University of Michigan. 1947.

10-49 Blandy, W. H. P., Circular Letter NavOrd OCL F11-43. U. S. Navy Bureau of Ordnance. October 25, 1943.

10-50 Blasdel, I. C., and Lazo, J., Study of Exterior Lighting for Navy Airplanes. Part 5. Report TED NAM 31333. U. S. Naval Air Experimental Station, Naval Air Materiel Center, Philadelphia, Pa. May 31, 1947.

10-51 Bromer, J. A., and Orlansky, J., Preliminary Report on Investigation of Exterior Lighting Equipment. Part I. Report TED NAM 31333. U. S. Naval Air Experimental Station, Naval Air Materiel Center, Philadelphia, Pa. August 1945.

10-52 Brown, C. R., and Gebhard, J. W., "Visual Field Articulation in the Absence of Spatial Stimulus Gradients." J. Exp. Psychol. Vol. 38. 1948. pp. 188-200.

10-53 Brown, R. H., The Visual Discrimination of Velocity as a Function of the Rate of Movement and Other Factors. Naval Research Laboratory Report No. 4299. January 26, 1954.

10-54 Brown, R. H., and Guedry, F. E., Jr. Influence of Visual Stimulation of Habituation to Rotation. U. S. Naval Air Station, Pensacola, Fla. January 10, 1950.

10-55 Campbell, P. A., Aircraft Observation by Sun Glare. USAF School of Aviation Medicine, Randolph Field, Texas. June 24, 1942. (CONFIDENTIAL)

10-56 Carpenter, C. R., Army-Navy-OSRD Vision Committee, Minutes and Proceedings of the Third Meeting. June 16, 1944. pp. 10-11. (CONFIDENTIAL)

10-57 Chandrasekhar, S., and Elbert, D. D., "The Illumination and Polarization of the Sunlit Sky on Rayleigh Scattering." Trans. Amer. Philosophical Soc. Vol. 44. Part 6. December 1954.

10-58 Chandrasekhar, S., and Elbert, D. D., "Polarization of the Sunlit Sky." Nature. Vol. 167. January 13, 1951. pp. 51-63.

10-59 Clark, B., Graybiel, A., and MacCorquodale, K., "Illusory Rotation of a Target during Turns in an Aircraft." Amer. J. Psychol. Vol. 61. 1948. pp. 50-58.

10-60 Clark, R. E., Visual Acuity through Colored Lenses. Commonwealth Fund Report No. 22 Tufts College M.A. Thesis. Office of Naval Research. Special Devices Center. 1943.

10-61 Clark, R. E., Visual Acuity for Different Wave Lengths of Monochromatic Light. Excerpt from M.A. Thesis at Tufts College.

10-62 Coblentz, W. W., and Stair, R., Spectral-Transmissive Properties and Use of Colored Eye-Protective Glasses. National Bureau of Standards Circular C421. June 1, 1938.

10-63 Corner, J. P., and Ganoung, R. E., "An Experimental Determination of the Visual Thresholds at Low Values of Illumination." J. Opt. Soc. Amer. Vol. 25. 1935. pp. 287-294.

10-64 Craik, K. J. W., Form Perception during Dark Adaptation. Great Britain. Flying Personnel Research Committee Report No. 193. October 1940.

10-65 Craik, K. J. W., and Vernon, M. D., Report on the Perception of Stationary and Moving Airplane Silhouettes in Plain and Clouded Fields. Great Britain. Flying Personnel Research Committee Report No. 326. July 1941.

10-66 Crumley, L. M., and Atkinson, W., Human Engineering Investigation of the Exterior Lighting of Naval Aircraft. Part I. Report TED NAM EL 52003. U. S. Naval Air Experimental Station, Naval Air Materiel Center, Philadelphia, Pa. September 23, 1954.

10-67 Culver, F. R., Water Clarity Nomographs. Scripps Institute of Oceanography, Reference 53-46. University of California. July 15, 1953.

10-68 DeGroot, S. G., Dodge, J. M., and Smith, Jo Ann., Factors in Night Vision Sensitivity: III. The Interrelation of Size, Brightness, and Location. U. S. Naval Submarine Base, New London, Conn. Medical Research Laboratory. No. 10. Report No. 234. BuMed & Surg. Project NM 003 041.09.05. September 14, 1953.

10-69 DeGroot, S. G., Dodge, J. M., and Smith, J. A., Factors in Night Vision Sensitivity: The Effect of Brightness. U. S. Naval Submarine Base, New London, Conn. Medical Research Laboratory. No. 11. Report No. 194. BuMed & Surg. Project NM 003 014.09.04. March 18, 1952.

10-70 Dubrovner, R., and Searle, L. V., The Pinpointer Technique and its Use in the Study of Target Identification. Project 506-008-0006. Tech. Report 53-19. HRRC, Air Research and Development Command, Mather Air Force Base, Calif. June 1953.

10-71 Ellerbrock, V. J., "Magnification for Near Vision." Engineering Experimental Station News. (Ohio State University). Vol. 25. 1953. pp. 28-37.

10-72 Elliot, A. J., "Significance of Aneiseikonia in Aviation." Trans. Canada Ophthal. Soc. September 1942 and Arch. Ophthal. Vol. 35. 1946. pp. 354-360.

10-73 Ellson, D. G., and Taylor, H. A., OSRD No. 4380. OEMsr-1171. Project N-114. Report No. 11. November 27, 1944.

10-74 Emson, R. H. E., Ref. FC, S.31752. Arm. Royal Air Force Fighter Command Hq. March 15, 1943. (CONFIDENTIAL)

10-75 Engle, G. E., and Marlow, W. C., AD-19814. Contract AF33(616)307. Project MI-1976. Fairchild Engine and Airplane Corporation, Fairchild Aircraft Div., Hagerstown, Md.

10-76 Farnsworth, D., Standards for General Purpose Sun Glasses. U. S. Naval Submarine Base. New London. Conn. Medical Research Laboratory Report No. 140. Color Vision Report No. 17. BuMed Project NM 000 009. September 10, 1948.

10-77 Fiorentine, A., Jeanne, M., and DiFrancia, G. T., Measurements of Differential Threshold in the Presence of a Spatial Illumination Gradient. Dell'Instituto Nazionale di Ottica, Firenze, Italy. No. 683. Serie II, 3-11 1955.

10-78 Foitzik, L., Theory of Slant Visibility. Armed Forces-National Research Council Vision Committee. July 1, 1952.

10-79 Foitzik, L., "Ueber die Lichtdurchlässigkeit der stark getrübten Atmosphäre im sichtbaren Spektralbereich." (On the Transparency of a Strongly Turbid Atmosphere to Light in the Region of the Visible Spectrum: (English abstract) Deutsches Reichsamt für Wetterdienst. Wissenschaftliche Abhandlungen 4. No. 5. Berlin 1938.

10-80 Fox, W. C., Signal Detectability: A Unified Description of Statistical Methods Employing Fixed and Sequential Observation Processes. University of Michigan Engineering Research Institute. Project M970. Report No. 19. Electronic Defense Group, Contract No. DA-36-039 sc-15358. Army Project No. 3-99-04-042. Signal Corps Project No. 29-19B-0. December 1953.

10-81 Fry, G. A., and Allen, M. J., Effect of Flashes of Light on Night Visual Acuity. II. WADC Tech. Report 52-10. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. November 1951.

10-82 Fry, G. A., and Alpern, M., Effect of Flashes of Light on Night Visual Acuity. I. WADC Tech. Report 52-10. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. November 1951.

10-83 Fry, G. A., and Alpern, M., "The Effect of a Peripheral Glare Source upon the Apparent Brightness of an Object." J. Opt. Soc. Amer. Vol. 43. March 1953. pp. 189-19?.

10-84 Fry, G. A., and Alpern, M., "Effect of Veiling Luminance upon the Apparent Brightness of an Object." Amer. J. Optom. Vol. 31. 1954. pp. 506-520.

GENERAL BIBLIOGRAPHY (Cont)

10-85 Fry, G. A., and Ihrig, N., Effect of Flashes of Light through the Closed Eyelid. Part I. Preservation of Dark Adaptation during a Flash by Closing the Eyelids. WADC Tech. Report 53-150. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. March 1953.

10-86 Fry, G. A., and Ihrig, N., Effect of Flashes of Light through the Closed Eyelid. Part 2. Use of Dark Grease on the Closed Eyelids as a Means of Preserving Dark Adaptation during a Flash of Light. WADC Tech. Report 53-159. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. February 1953.

10-87 George, F. H., "Errors of Visual Recognition." J. Exp. Psychol. Vol. 43. 1952. pp. 202-206.

10-88 Gerathewohl, S. J., and Haber, H., Study on the Efficiency of Aircraft Insignia and Aircraft Markings. Project Report. USAF School of Aviation Medicine, Randolph Field, Texas. August 1950.

10-89 Gilinsky, A. S., "The Effect of Attitude upon the Perception of Size." Amer. J. Psychol. Vol. 68. June 1955. pp. 173-192.

10-90 Gilinsky, A. S. "Perceived Size and Distance in Visual Space." Psychol. Rev. Vol. 58. November 1951. pp. 460-482.

10-91 Gilinsky, A. S., and Brown, J. L., Eye Dominance and Tracking Performance. WADC Tech. Report 52-16. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. April 1952.

10-92 Goldie, E. A. G., Methods of Measurement of Gunflash in Aircraft Weapons with Special Reference to the Visual Method. OSRD No. WA-681-3. Royal Air Force Physiological Laboratory, Farnborough, England. May 3, 1943.

10-93 Goldie, E. A. G., Note on Recognition of Coloured Signal Lights through Crookes (Neutral) and a Greenish Tinted Filter (Chance 351/13 for Use in Anti-Glare Spectacles). OSRD No. WA-1323-6. Report 38/35. Royal Air Force Physiological Laboratory, Farnborough, England. November 17, 1943.

10-94 Grant, D. A., and Mote, F. A., "Effects of Brief Flashes of Light upon the Course of Dark Adaptation." J. Exp. Psychol. Vol. 39. 1949. pp. 610-615.

10-95 Graybiel, A., Clark, A., MacCorquadale, R., and Hupp, D. I., The Role of Vestibular Nystagmus in the Visual Perception of a Moving Target in the Dark. Project No. X-148 (Av-4-3) Report 5. January 14, 1946.

10-96 Greene, G. M., Project No. PTR-31782. U. S. Naval Air Station, Patuxent River, Md. April 25, 1945. (CONFIDENTIAL)

10-97 Greene, G. M., Project TED No. PTR-2406. U. S. Naval Air Station, Patuxent River, Md. December 7, 1944. (CONFIDENTIAL)

10-98 Guth, S. K., "Visibility." G-E Review. May 1952.

10-99 Haber, H., "Man and Machine between Atmosphere and Space." Aero. Engng. Rev. Vol. 13. November 1954. pp. 56-62.

10-100 Haber, H., The Physical Environment of the Flyer. USAF School of Aviation Medicine, Randolph Field, Texas. 1954.

10-101 Hahn, E. L., and Bartley, S. H., "The Apparent Orientation of a Luminous Figure in Darkness." Amer. J. Psychol. Vol. 67. 1954. pp. 500-508.

10-102 Halsey, R. M., Curtis, C. E., and Farnsworth, D., Field Study of Detectability of Colored Targets at Sea. Laboratory Report No. 265. Vol. 14. BuMed & Surg. U. S. Navy, New London, Conn. May 26, 1955.

10-103 Hanes, R. M., "Some Effects of Shape on Apparent Brightness." J. Exp. Psychol. Vol. 40. October 1950. pp. 650-654.

10-104 Harry, C. H., and Taffel, S. L., Report No. DR-1467. Navy Department, Bureau of Aeronautics. Washington, D. C. 1953. (CONFIDENTIAL)

10-105 Hartline, H. K., and McDonald, R., Frequency of Seeing at Low Illumination. Report No. 110. U. S. National Research Council, Committee on Aviation Medicine. January 1943.

10-106 Hartline, H. K., and McDonald, R., Use of Ultra-Violet Absorbing Goggles in Aircraft at Night. Report No. 64. U. S. National Research Council, Committee on Aviation Medicine. August 12, 1942

10-107 Hecht, S., and Hendley, C. D., The Effect of Sunlight on Night Vision. Report No. 420. U. S. National Research Council, Committee on Aviation Medicine. March 24, 1945.

10-108 Helson, H., and Grove, J., "Changes in Hue, Lightness, and Saturation of Surface Colors in Passing from Daylight to Incandescent-Lamp Light." J. Opt. Soc. Amer. Vol. 37. 1947. pp. 387-395.

10-109 Hillman, B., Report on Testing and Evaluation of Bausch and Lomb Neutral N-15 Sunglasses. U. S. Naval Submarine Base. Medical Research Laboratory, Visual Engng. Sect., New London, Conn. March 1953.

10-110 Hillman, B., Connolly, K., and Farnsworth, D., Color Perception of Small Stimuli with Central Vision. Report No. 257. U. S. Naval Submarine Base. Medical Research Laboratory. BuMed & Surg. Navy Dept. Project NM 002 014.09 02. October 1954.

10-111 Hopkinson, R. G., and Petherbridge, P., "Two Supplementary Studies on Glare." Trans. Illum. Engng. Soc. London. Vol. 19. 1954. pp. 220-224.

10-112 Hopkinson, R. G., The Brightness of the Environment and its Influence on Visual Comfort and Efficiency. Building Research Conference. 1951. pp. 133-138.

10-113 Horowitz, M. W., and Kappauf, W. E., Aerial Target Range Estimation. OSRD No. 5301. U. S. Office of Scientific Research and Development. National Defense Research Committee. Appl. Psychol. Panel. July 3, 1945.

10-114 Hulburt, E. O., Advances in the Physics of the Upper Air Since 1950. Report No. 4600. U. S. Naval Research Laboratory. October 25, 1955.

10-115 Hulbert, E. O., "Explanation of the Brightness and Color of the Sky Particularly the Twilight Sky." J. Opt. Soc. Amer. Vol. 43. February 1953. pp. 113-118.

10-116 Hulburt, E. O., Survey of the Brightness of the Night Sky. Reprint of NRL Report N-4203. Naval Research Laboratory. April 1948.

10-117 Hulburt, E. O., Report No. H-2494. U. S. Naval Research Laboratory. April 12, 1945. (CONFIDENTIAL)

10-118 Jenkins, W. O., Army-Navy-OSRD Vision Committee, Minutes and Proceedings of the Fourth Meeting. July 27, 1944. pp. 37-42. (CONFIDENTIAL)

10-119 Justus, G. M., Nokle, H. A., and Gross, W. A., Range and Speed Estimation. Project TT 2-689. Third Report, Dates of Test: July 18 to July 28, 1952. Aberdeen Proving Ground, Md. October 1953.

10-120 Karandikar, R. V., "Luminance of the Sun." J. Opt. Soc. Amer. Vol. 45. No. 6. June 1955. pp. 483-488.

10-121 Kaufman, E. L., Lord, M. W., Reese, T. W., and Volkmann, J., "The Discrimination of Visual Number." Amer. J. Psychol. Vol. 62. 1949. pp. 498-525.

10-122 Keil, F. K., Apparent Size of Aircraft at Various Altitudes. Army Air Force School of Aviation Medicine, Randolph Field, Texas. June 1942.

10-123 Kennedy, John L., and Travis, R. C., "Prediction and Control of Alertness. II. Continuous Tracking." J. Compar. Physiol. Psychol. Vol. 41. June 1948. pp. 203-209.

10-124 Kincaid, W. M., An Analysis of Aerial Visual Surveillance Capabilities. Research Report 4. University of Michigan Vision Research Laboratory. 1955.

10-125 Krauskopf, J., Duryea, R. A., and Bitterman, M. E., "Threshold for Visual Form: Further Experiments." Amer. J. Psychol. Vol. 67. September 1954. pp. 427-440.

10-126 Lacy, O. W., Lewinger, N., and Adamson, J. F., "Fore Knowledge as a Factor Affecting Perceptual Defense and Alertness." J. Exp. Psychol. Vol. 45. 1953. pp. 169-174.

10-127 Lauer, A. R., Filter Study of the Effect of Certain Transmission Filters on Visual Acuity with and without Glare. Highway Research Board Bull. No. 43. National Research Council, Div. of Engineering and Industrial Research, Washington, D. C. 1951. pp. 45-51.

10-128 Lauer, A. R., and Silver, E. H., "Certain Factors Influencing the Tolerance of Light and Visual Acuity." Iowa Acad. of Science. Vol. 52. 1945. pp. 265-270.

10-129 Laun, J., Exterior Color Schemes for Aircraft to Provide Maximum Visibility. Report TED NAM AE-4298. Investigation of Color Schemes to Improve Propeller Noticeability. Naval Air Materiel Center. May 1954.

10-130 Lichte, W. H., "Shape Constancy: Dependence upon Angle of Rotation; Individual Differences." J. Exp. Psychol. Vol. 43. 1952. pp. 49-57.

10-131 Lincoln, R. S., and Smith, Karl U., "Systematic Analysis of Factors Determining Accuracy in Visual Tracking." Science. Vol. 116. 1952. pp. 183-187.

10-132 Livingston, P. C., The Visual Problems of Night Interception. Report No. 297. Great Britain. Flying Personnel Research Committee. April 1941.

10-133 Low, F. N., Peripheral Visual Acuity: A Review. Office of Naval Research. Navy Dept. Johns Hopkins University. June 30, 1950.

10-134 Low, F. N., Effect of Training on Acuity of Peripheral Vision. Report No. 68. Civil Aeronautics Administration, Div. of Research. 1946.

10-135 Luckiesh, M., and Moss, F. K., "The Ability to See Low Contrasts at Night." J. Aeronaut. Sci. Vol. 9. 1942. pp. 261-263

10-136 Ludvigh, E., and Miller, J. W., An Analysis of Dynamic Visual Acuity in a Population of 200 Naval Aviation Cadets. Joint Project Report No. NM 001075.01.07. U. S. Naval School of Aviation Medicine, Pensacola, Fla. December 22, 1954. p. 18.

10-137 Ludvigh, E., Perception of Contour: I. Introduction. Contract Nonr-586(00). U. S. Naval School of Aviation Medicine, Pensacola, Fla. August 1953.

10-138 Ludvigh, E., and Miller, J. W., The Effects of Dynamic Visual Acuity of Practice at One Angular Velocity on the Subsequent Performance at a Second Angular Velocity. U. S. Naval School of Aviation Medicine, Pensacola, Fla. June 1955.

10-139 Ludvigh, E., and Miller, J., Some Effects of Training on Dynamic Visual Acuity. U. S. Naval Air Station, Pensacola, Fla. School of Aviation Medicine and Research. Report No. 6. Office of Naval Research. Kresge Eye Institute. September 1954.

10-140 Ludvigh, E., and Miller, J. W., A Study of Dynamic Visual Acuity. Joint Project Report No. NM 001 067.01.01. U. S. Naval School of Aviation Medicine, Pensacola, Fla. March 4, 1953.

10-141 Ludvigh, E., and Miller, J. W., A Study of Dynamic Visual Acuity. Joint Project Report No. 1. U. S. Naval School of Aviation Medicine, Pensacola, Fla. 1957.

10-142 MacKenzie, M. H., Kohls, F. F., Cronin, H. E., and Seaton, S. L., Twilight and Airglow Study. Geo-Science, Inc., Washington Grove, Md. AF Contract AF 19(122)-433, U. S. Air Force, Air Research and Development Command. Air Force Cambridge Research Center. February 1, 1953, for period January 1951 to January 1953.

10-143 Mackworth, N. H., Great Britain Flying Personnel Research Committee. Report No. 586(a). Great Britain OSRD No. WA-5530-1F. April 1945.

10-144 Mahler, W. R., and Bennett, G. K., Psychological Studies of Advanced Naval Air Training: Evaluation of Operational Flight Trainers. Special Devices Center Human Engineering, Psychological Corp. September 1, 1950.

10-145 Mahler, W. R., and Bennett, G. K., Psychological Studies of Advanced Naval Air Training: Analysis of Flight Performance Ratings. Special Devices Center Human Engineering. Psychological Corp. September 1, 1950.

10-146 Mallett, F. S., Problems and Control of Air-Pollution. Reinhold Publishing Corp. 1955.

10-147 McGuire, J. C., The Effect of Target Velocity and the Area of Error-Tolerance Circles upon Performance in a Two-Dimensional Compensatory Tracking Task. WADC Tech. Report 54-431. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. 1954.

10-148 Merton, W. R., Great Britain Royal Air Force Coastal Command, Operational Research Sect. Report No. 151.

10-149 Middleton, W. E. K., "Estimation and Measurement of the Visual Range." Royal Meteorological Soc. Vol. 3. October 1952. pp. 1-12.

10-150 Miles, W., Army-Navy-OSRD Vision Committee, Minutes and Proceedings of the Eighth Meeting. December 12, 1944. pp. 16-19. (CONFIDENTIAL)

10-151 Miles, W. R., "Red Goggles for Producing Dark Adaptation." Federation Proceedings. Vol. 2. 1943. pp. 109-115.

10-152 Miller, R., Sky Brightness Measurements at 20,000 25,000 and 30,000 Ft. Northrop Aircraft Inc. November 1951. (CONFIDENTIAL)

10-153 Mitchell, R. T., Morris, A., and Dimmick, F. L., The Relation of Dark Adaptation to Duration of Prior Red Adaptation. Report No. 166. Vol. 9. 1950. pp. 258-277. Medical Research Laboratory. U. S. Naval Submarine Base, New London, Conn. BuMed. Project NM 003 041.49.01. December 6, 1950.

10-154 Mobile, C. E., The Perception of the Vertical: IV. The Visual Vertical as a Function of Centrifugal and Gravitational Forces. Project No. NM001-037. U. S. Naval School of Aviation Medicine and Research. September 10, 1949.

10-155 Moller, F., Über die Farbe der Sicht und des Tageshimmels. (Color Vision and the Daylight Sky) (In German with English Summary). Arch. für Meteorologie, Geophysik u. Bioklimatologie, Series B: General Biological Climatology. Vol. 5. No. 1. 1953.

10-156 Noble, C. E., The Perception of the Vertical; IV. The Visual Vertical as a Function of Centrifugal and Gravitational Forces, Joint Project Report No. 7., Tulane University. Contract N7onr-434 Task Order I, Office of Naval Research. Project Designation NR 140-455. U. S. Naval School of Aviation Medicine and BuMed & Surg. Project NM 001 037. September 10, 1949.

10-157 Page, H. E., Vertigo Incidence among Naval Aviators. Project NM 001 063.01.16. Joint Project Report No. 61. U. S. Naval Air Station, Pensacola, Fla., School of Aviation Medicine and Research. March 15, 1950.

10-158 Passey, G. E., "The Perception of the Vertical: V. Adjustment to the Vertical with Normal and Tilted Visual Frames of Reference" J. Exp. Psychol. Vol. 40. No. 6. December 1950. pp. 738-745.

10-159 Passey, George E., The Perception of the Vertical: 9. Adjustment of the Visual Vertical from Various Magnitudes of Body Tilt. Project NM 001063.01.15. Joint Project Report No. 15. U. S. Naval Air Station, Pensacola, Fla., School of Aviation Medicine and Research. March 10, 1950.

10-160 Passey, G. E., and Guedry, F. E., Jr., "The Perception of the Vertical: II. Adaptation Effects in Four Planes." J. Exp. Psychol. Vol. 39. 1949. pp. 700-710.

10-161 Passey, G. E., and Ray, J. T., The Perception of the Vertical: 10. Adaptation Effects in the Adjustment of the Visual Vertical. Project NM 001 063.01.17. Joint Project Report No. 17. U. S. Naval Air Station, Pensacola, Fla., School of Aviation Medicine and Research. October 20, 1950.

10-162 Pearl, B. E., Simon, J. R., and Smith, K. U., "Visual Tracking: IV. Interrelations of Target Speed and Aided-Tracking Ratio in Defining Tracking Accuracy." J. Appl. Psychol. Vol. 39. 1955. pp. 209-214.

10-163 Peckham, R. H., The Influence of Sun Glasses on Object-Color Perception. Contract N8 onr 560. Project NR 142-565m. Final Report. September 1949.

10-164 Peckham, R. H., Army-Navy-OSRD Vision Committee, Minutes of the Tenth Meeting. March 18, 1945. pp. 17-2? (CONFIDENTIAL)

10-165 Peckham, R. H. Army-Navy-OSRD Vision Committee, Minutes and Proceedings of the Fifth Meeting. September 18, 1944. pp. 12-28. (CONFIDENTIAL)

10-166 Peckham, R. H., West, H., Henry, C. E., and Clark, W. B., Methodology in Determining Scotopic Flash Limens. U. S. Naval Air Station Medical and Research Report. January 18, 1944

10-167 Pendorf, R., Goldberg, B., and Lufkin, D., Slant Visibility. USAF, Air Research and Development Command, Air Force Cambridge Research Center, Cambridge, Mass. Geophysics Research Directorate, Geophysics Survey No. 21. December 1952.

10-168 Pfefferkorn, R. G., and Lauer, A. R., "Changes in Position of Presentation as Related to Perceptual Efficiency in Stimulus Identification." Proc. Iowa Acad. Sci. Vol. 61. 1954. pp. 406-412.

10-169 Phillips, F. C., and Knowles, M. D., The Variation in Range of Visibility of Four Engined Aircraft Silhouettes with Changes in Night Sky Brightness. Report No. 155. OSRD No. WA-1777-2. Great Britain Ministry of Aircraft Production, Aircraft and Armament Experimental Establishment, Boscombe Down. January 22, 1944.

10-170 Pinson, Ernest, and Chapanis, A., "The Relationship between Measures of Night Vision and Dark Adaptation." Fed. Proceedings. Vol. 5. No. 1. March 1946.

10-171 Pinson, E. A., and Chapanis, A., Form Discrimination at Low Illumination. U. S. Army Air Forces, Materiel Center, Engineering Div., Aero Medical Laboratory. February 6, 1943.

10-172 Pirenne, M. H., Great Britain. Report 45/431. Medical Research Council, Military Personnel Research Committee, Bodily Protection Committee, Sub-Committee on Armoured Fighting Vehicles. June 24, 1945. Great Britain OSRD No. WA-5424-6.

10-173 Pollock, W. T., "The Visibility of a Target as a Function of its Speed of Movement." J. Exp. Psychol. Vol. 45. June 1953. pp. 449-454.

10-174 Poulton, E. C., Perceptual Anticipation in Tracking. Great Britain. A.P.U. 118/50. Medical Research Council, Applied Psychology Research Unit, Psychological Laboratory, Cambridge. August 1950.

10-175 Poulton, E. C., and Gregory, R. L., Blinking during Visual Tracking. Great Britain. A.P.U. 152.51. Medical Research Council, Applied Psychology Research Unit, Psychological Laboratory, Cambridge. June 1951.

10-176 Ray, James T., and Niven, J. I., The Perception of the Vertical: 12. The Point of Shift from Visual to Postural Frames of Reference. Joint Research Report No. 21. U. S. Naval Air Station, Pensacola, Fla., School of Aviation Medicine and Research. February 8, 1951.

10-177 Reid, D. D., "Night Visual Capacity and its Relation to Survival in Operational Flying." Brit. J. Psychol. Vol. 3, Part 3. 1950. pp. 141-150.

10-178 Richards, W. J., Shuford, E. H., Bickle, A. J., et al., Reaction Times in Response to Light Stimuli. Arkansas University Tech. Report No. 22. September 1953.

10-179 Riggs, L. A., Mueller, C. G., Graham, C. H., and Mote, F. A., "Photographic Measurements of Atmospheric Boil." J. Opt. Soc. Amer. Vol. 37. 1947. pp. 415-420.

10-180 Riggs, Lorrin A., Ratliff, Floyd, Cornsweet, Janet C., and Cornsweet, Tom N., "The Disappearance of Steadily Fixated Visual Test Objects." J. Opt. Soc. Amer. Vol. 43. June 1953. pp. 495-501.

10-181 Riopelle, Arthur J., "Dispersion of Stimulus-Areas and the Scotopic Threshold." Amer. J. Psychol. Vol. 64. July 1951. pp. 380-390.

10-182 Romejko, Walter J., Effect of Fields of Vision from Fighter Aircraft on the Number and Rate of Accidents. Memorandum Report. U. S. Army Air Forces, Air Technical Service Command, Engineering Div. September 11, 1945.

10-183 Rowland, Louise Sloan, Night Visual Efficiency in Illuminations above the Level of the Cone Threshold. Project No. 258. Report No. 1. U. S. Army Air Force School of Aviation Medicine, Randolph Field, Texas. May 31, 1944.

10-184 Rowland, Louise S., Intensity as a Factor in Recognition of Colored Light Signals. Project No. 37. Report No. 1. U. S. Army Air Force School of Aviation Medicine, Randolph Field, Texas. August 1942.

10-185 Saltzman, D. C., and Garner, W. R., "Accuracy of Visual Estimation of Azimuth Position." J. Psychol. Vol. 29. 1950. pp. 453-467.

10-186 Schaefer, Cl., Kliefoth, W., and von Wolff-Breslau, Th.,"Influence of Colored Glass Filters on Visibility Resulting from Variation of Luminance Contrast, Hue Contrast, and Saturation Contrast." Z. f. Tech. Physik. Vol. 24. 1943. pp. 125-140. Translated from German, Translation No. T-1379.

10-187 Schaefer, H. J., Exposure Hazards from Cosmic Radiation Beyond the Stratosphere and in Free Space. Project NM 001 059.13.03. U. S. Naval School of Aviation Medicine, Pensacola, Fla. March 1952.

10-188 Scobee, R. G., and Rowland, W. M., Demon Dazzle in Night Vision. Project 377. Report 1. U. S. Army Air Force School of Aviation Medicine, Randolph Field, Texas. April 1945.

10-189 Sexton, Mary, Malone, Florence, and Farnsworth, Dean, The Effect of Ultra-Violet Radiation from Fluorescent Lights on Dark Adaptation and Visual Acuity. Report No. 169. Medical Research Laboratory. U. S. Naval Submarine Base, New London, Conn. Vol. 9. 1950. pp. 301-317. BuMed Project NM 003 041.38.01. December 20, 1950.

10-190 Sharp, L. H., Gordon, D., and Reuder, M., Review of Studies on the Effect of Training on Night Vision Ability. Army Project No. 29530100, PJ 3001-06, PRS Report 974. Dept. of the Army, Personnel Research Section, PR & PBr-Pers. Bur., TAGO, Washington, D. C. August 1952.

10-191 Shilling, C. W., Handbook on Night Lookout Training. Medical Research Laboratory. Atlantic Fleet. U. S. Naval Submarine Base, New London, Conn. May 1, 1943. Revision 1, September 1, 1943.

10-192 Shilling, C. W., and Verplanck, W. S., Use of Binoculars at Night. Medical Research Laboratory. U. S. Naval Submarine Base, New London, Conn. August 31, 1943. (CONFIDENTIAL)

10-193 Siedentopf, H., Kraus, David, and Penndorf, Rudolph, Light in the Troposphere. (Photometric and Radiometric Measurements in the Troposphere with Application to the Visibility of Aerial Targets and Stars in the Daylight Sky). AFCRL-TR-55-210. U. S. Air Force, Air Research and Development Command, Air Force Cambridge Research Center, Cambridge, Mass. July 1955.

10-194 Simonson, Ernst, Blandstein, Samuel S., and Carey, Eben J., "The Efficiency of the Glare Reduction by the Eyelids." Amer. J. Physiol. Vol. 143. 1944. pp. 541-547.

10-195 Slater-Hammel, A. T., "Reaction Time to Light Stimuli in the Peripheral Visual Field." (Indiana University) Res. Quart. Vol. 26. 1955. pp. 82-87.

10-196 Strand, Kaj G., Investigation of Atmospheric Refraction at Low Altitudes. ADTIC Publ. No. A-102. Arctic, Desert, Tropic Information Center, Air University, Maxwell Air Force Base, Ala. February 1953.

10-197 Tousey, R., U. S. Naval Research Laboratory Report No. H-2226. January 31, 1944. (CONFIDENTIAL)

10-198 Tousey, R., U. S. Naval Research Laboratory Report No. H-2034. March 30, 1944. (CONFIDENTIAL)

10-199 Tousey, R., Hulburt, E. O., and Friedman, H., U. S. Naval Research Laboratory Report No. H-2303. June 6, 1944.

10-200 Tousey, R., and Koomen, M. J., The Visibility of Stars at Twilight. U. S. Naval Research Laboratory, Washington, D. C.

10-201 von Tschermak-Seysenegg, A., and Heinsius, E., Ueber Nachtsehproben mit Leuchtfarbe. (Concerning Night Vision Experiments with Luminous Materials). U. S. Navy, Office of Chief of Naval Operations, Intelligence Division, captured German document, Intelligence Report, Germany. Medical Research Div., Naval Sanitation Station, Ostsee, Berlin. 1943.

10-202 Vernon, M. D., Further Experiments on the Assessment of 'Perceptual Ability'. Great Britain. MRC 47/96. Medical Research Council, Applied Psychology Research Unit, A.P.U. 32, Psychological Laboratory, Cambridge. Vol. 29. No. 1. January 1946.

10-203 Vernon, M. D., The Assessment of 'Perceptual Ability'. Great Britain. MRC 47/151. Medical Research Council, Applied Psychology Research Unit, A.P.U. 29, Psychological Laboratory, Cambridge. July 1945.

10-204 Vernon, M. D., Report on Learning to Identify Aeroplanes from Photographs. Flying Personnel Research Committee Report No. 382. Medical Research Council. November 24, 1941.

10-205 Vernon, M. D., The Ability to Distinguish Dimly Illuminated Aeroplane Silhouettes. Great Britain. Flying Personnel Research Committee Report No. 247. January 1941.

10-206 Vezey, E. E., and Evans, B. H., "The Study of Natural Illumination by Means of Models under an Artificial Sky." Illum. Engng. Vol. 50. No. 8. August 1955. pp. 367-374.

10-207 Vinache, W. E., Vertigo as Experienced by Naval Aviators. Project No. X-148 (Av-4-3). Report No. 13. July 3, 1946.

10-208 Wagner, H. G., Blasdel, Irene C., and Lazo, J., Study of Exterior Lighting for Navy Airplanes. IV. A Method of Exterior Aircraft Illumination Using Transparent Acrylic Plastic. Report No. TED NAM 31333. Naval Air Materiel Center, Naval Air Experimental Station, Philadelphia, Pa. February 1949.

10-209 Waldram, J. M., "Measurement of the Photometric Properties of the Upper Atmosphere." Trans. Illum. Engng. Soc. Vol. 10. No. 8. August 1945. pp. 146-187.

10-210 Walker, E. L., Investigation of Visual Factors Contributing to Night Aircraft Accidents, with Special Reference to Methods of Lighting Planes. Project No. X-498 (Av-265-P). Report No. I. U. S. Naval Air Training Bases, Medical Department, Corpus Christi, Texas. July 1945.

10-211 Warrick, M. J., et al., Effect of Moderate Positive Acceleration on Ability to Read Aircraft-Type Instrument Dials. Memo Report No. TSEAA 694 10. USAF Air Materiel Command. November 1946.

10-212 Wedell, C. M., Final Report in Summary of Work on the Selection and Training of Night Lookouts. OSRD No. 4342. Report No. 4. U. S. Office of Scientific Research and Development. National Defense Research Committee., Appl. Psychol. Panel, Princeton, University. November 15, 1944.

10-213 Wedell, C. M., A Study of the Prediction of Night Lookout Performance. OSRD No. 3357. Report No. 1. U. S. Office of Scientific Research and Development. National Defense Research Committee, Appl. Psychol. Panel, Princeton University. March 15, 1944.

10-214 Weston, H. C., The Relation between Illumination and Visual Efficiency - The Effect of Brightness Contrast. Great Britain. Report No. 87. OSRD Liaison Office Reference No. WA-4040-11A. Medical Research Council, Industrial Health Research Board. 1945.

10-215 Wickiser, R. L., Project TED No. PTR-2570. U. S. Naval Air Station, Patuxent River, Md. January 13, 1945.

10-216 Wilkins, M. H. F., Great Britain. Ministry of Home Security, Civil Defense Research Committee, Subcommittee C (Luminescent Materials) Report RV(C) 44. Great Britain OSRD No. II-5-133. July 23, 1941. (CONFIDENTIAL)

10-217 Wing, Cliff, W., Jr., and Passey, George E., The Perception of the Vertical: 11. The Visual Vertical under Conflicting Visual and Acceleratory Factors. Project NM 001 063.01.20. Joint Project Report No. 20. U. S. Naval Air Station, Pensacola, Fla., School of Aviation Medicine and Research. November 15, 1950.

CHAPTER 11

AIR-TO-GROUND VISIBILITY

Air-to-ground visibility is crucial in take-off and landing, in visual navigation, bombing, reconnaissance, and search. In all these operations, the visual task involves detecting objects on the sea or ground, and usually it also involves identifying them. Whether the object is a beacon or mountain peak as in navigation, a warehouse as in bombing, or a downed plane as in search, the detection problem is essentially the same. It is true that, in navigation and bombing, one is dealing with larger objective targets than in reconnaissance and search; however, with current speeds and altitudes, large objects must be detected at such great distances that they may appear very small. In other words, the chief distinction between navigation, bombing, reconnaissance, and search is not the type of visual information required or the visual functions involved in getting it, but what is done with the information after it is obtained.

Whatever the mission, personnel searching from aircraft must be able to detect a tremendous variety of objects -- periscopes, camouflaged buildings, all types of ships, all kinds of landmarks for navigation -- against every conceivable kind of sea and land background. It will be seen in this chapter that problems abound, and that our knowledge of air-to-ground vision is not complete as yet.

In general, the ease with which a target is seen depends on six principal factors: (1) characteristics of the observer, (2) characteristics of his aircraft, (3) time of day, (4) meteorological conditions, (5) characteristics of the object or objects sought, and (6) the techniques used to search and identify. Characteristics of the aircraft are covered for all phases of flight under Vision Through the Windshield and Canopy in Chapter 9, Factors Influencing Vision Outside the Aircraft. The other five variables are discussed in the pages that follow. In this chapter, particular emphasis is placed on how detection and identification are influenced by the characteristics of the object and the techniques used. At the end of the chapter, problems associated with these variables are presented for specific missions. This presentation is in the form of a summary table. Often, one or another column in the table is empty, not because there are no problems, but because there are no data on them.

CHARACTERISTICS OF THE OBSERVER

By characteristics of the observer, we mean both the individual's basic visual capacities and such factors as the number of observers involved in the search.

Color Vision in Detecting Camouflage

To study color vision in its relation to detection of camouflage, two groups of color-defective and normal subjects were matched in flying experience, rank, and age.[11-20] Missions were flown in a B-26, and observations were made through the bomb-bay and side-gun vents. Irregular panels about nine by nine feet, painted in standard camouflage colors, were placed at different times against three backgrounds: grass, sand, and grass and sand. The subjects observed the panels from altitudes of 4000, 3000, 2000, and 1000 feet. Each subject counted the panels displayed. The score was the number of errors made. Two observations were made by each subject at each altitude. It was found that the ability to detect brightness differences is more help in finding camouflaged objects than the ability to detect color differences. However, subjects with normal color vision were slightly, but consistently, more efficient in detecting the panels than the color-defective subjects.

Factors Other Than Vision in Target Detection

Target identification calls for the use of several faculties besides vision. There is a tremendous difference between merely reporting that something has been seen and telling exactly what it is. In order to identify an object, the observer must know its characteristics. Learning, memory, and other psychological processes are thus brought into play when the individual must interpret what he sees. More specifically, two investigators[11-9] have analyzed the variations in performance among experienced observers during a ten-day field test. They found great difference in ability to carry out tactical aerial reconnaissance successfully. They conclude that there is a need for better crew selection and training in tactical reconnaissance.

Number of Observers

Since observers differ so markedly in their skill, one might ask whether it is advisable to employ a large number of observers on a single flight. The same investigators [11-9] found no significant differences in detection from single-seater and two-seater visual reconnaissance aircraft. On the other hand, other workers [11-8] tentatively recommended two-man reconnaissance aircraft in an earlier study.

Theoretically, the probability of detecting a small or camouflaged target is increased when an observer is added, as Table 11.1 shows. This table is of little use at present, because no data have been gathered on the probability on one observer detecting a target under given sets of conditions. However, the table may be helpful in the future, when data have been accumulated and field tests have been made to test the table's validity.

Table 11.1 Probabilities of Detecting Target for One and Two Observers*

A - Detection probabilities assumed equal for pilots and observers:

Probability that One Will Detect Target	Probability that Two Will Detect Target	Gain by Adding an Observer
0.05	0.097	94%
0.1	0.19	90%
0.2	0.36	80%
0.4	0.64	60%
0.6	0.84	40%
0.8	0.96	20%
0.9	0.99	10%
1.0	1.0	0

B - Percentage gained by adding observer when detection probabilities are unequal for pilot and observer:

Probability that Observer Will Detect Target	Percentage Gained When Pilot Detection Probabilities Are: 0.05	0.1	0.2	0.4	0.6	0.8	1.0
0.3	570%	270%	120%				
0.7	1330	630	280	105%	45%		
0.95	1800	850	380	180	60	25%	0%

*(Chapanis et al. [11-8])

TIME OF DAY AT WHICH FLIGHT OCCURS

Target detection is generally better by day than at night. At night, the color of objects (other than lights) is no longer a useful clue, forms are more difficult to distinguish, bright lights may suddenly appear and interfere with dark adaptation, and visibility in general is decreased. However, conditions by day are by no means uniformly favorable to visual detection. Shadows, haze, glare and reflections from water and snow, and many other factors affect vision by day. One of the night lookout's advantages over the day lookout is his greater absolute sensitivity to light. When he is fully dark-adapted, he can easily detect lights that cannot be seen in daylight.

An individual is sometimes exposed to an extreme range of illumination levels over a short period. On an overcast day, a jet pilot often climbs from low illumination into brilliant sunshine in a few minutes. Similar situations arise when personnel must alternate between outside search and reading interior displays.

In general, however, detection tasks are most effectively carried out between midmorning and midafternoon, just as in air-to-air search.

CHARACTERISTICS OF THE OBJECTS TO BE DETECTED

The properties of an object that determine how easily it can be detected or identified are difficult to analyze quantitatively. They vary greatly from one situation to another and appear in many different combinations. However, we can name and discuss these properties individually. The important ones are size and shape, brightness contrast, color contrast, complexity of the background, whether the object is stationary or moving and the number and density of objects being sought visually. These factors will be considered in the order given above.

Size of Object

When an object is small in actual size (e.g., a submarine periscope) or in subtended size (because it is far away or oriented so as to subtend a small visual angle) detection is extremely difficult. Some evidence of size of target vs. detection is provided by two investigators.[11-7] They investigated the variables that affect an observer's ability to pick out critical targets in a heterogeneous array. Three observers viewed a complex array of forms under varying conditions of distance, exposure time, number of forms, and brightness contrast. Forty-six forms, both rectilinear and curvilinear, were used. The percentage of correct responses in picking out certain rectilinear figures was tabulated. The results show that the probability of correct response decreased linearly with the distance between the subject and the target. An interesting finding was that a form that could be picked out only at a high contrast -- 100 percent -- when it was 0.6 inch wide could be picked out at a very low contrast -- 7 percent -- when its width was increased to 1 inch. That is, a small increase in area compensated for a large reduction in contrast; in fact, the increase in area required to compensate for such a contrast reduction was much smaller than one would predict on the basis of detection data such as those[11-10] mentioned in Chapter 9.

Shape of Object

A study by one team[11-17] grew out of such practical problems as this: If several scattered areas of a dockyard are illuminated, will they be made more easily visible from the air than a single lighted area at the same level of illumination? In the experiment, the minimum perceptible brightness of a circular patch was compared with that of (a) an elliptical patch of the same area, and (b) a regular, circular group of circular patches of equal size and brightness. The patches were projected onto any one of 36 positions on the inside surface of a screen shaped like a section of a cylinder wall. The illumination of the patches was increased until they were seen by the dark-adapted subject. There were three subjects and two screen brightnesses: 3×10^{-6} candles/ft^2 for starlight and 52×10^{-5} candles/ft^2 for moonlight. This team found that the size of the lighted area, rather than its shape, determined visibility. It seems, therefore, that shape does not determine detectability as much as size.

Brightness Contrast

The brightness contrast between an object and its background is another important variable in detection. In some cases, size can be increased and contrast decreased, or vice versa, with no change in visibility. An example was the aforementioned finding[11-7] that increased size brought low-contrast performance nearly to the level of high-contrast detection. Another investigator[11-18] did an experiment in which white, gray, and black panels were laid out on the ground in the form of symbols. These were changed between each run of the aircraft used. The symbols were

The panels were either 8.6 by 1.4 feet, or 17 by 4 feet. The contrast provided by the white was 0.85 to 0.90; by the gray, 0.50 to 0.60. A pilot and three observers flew past the target on a predetermined course, with constant altitude for each run. Visibility on some runs was good, on others it was limited to 3 to 6 miles. The position of the target was known to the observers. The observers reported when the signal was (1) first seen, and (2) first legible. The results are shown in Table 11.2. Here we see that visibility (detection and identification) for aircraft increases as a function of increased brightness contrast.[11-18]

Table 11.2 Mean Ranges at Which Panels Were First Seen and First Legible, in Miles*

Altitude	Large White Panel: Good Vis.	Large White Panel: Vis. 3-6 miles	Small White Panel: Good Vis.	Small White Panel: Vis. 3-6 miles	Small Gray Panel: Good Vis.	Small Gray Panel: Vis. 3-6 miles
			First Seen			
2000 ft	2.4	2.1	1.8	-	1.1	1.1
4000	2.7	2.6	2.3	2.0	1.0	-
6000	3.8	2.9	2.6	2.2	-	-
			First Legible			
2000	1.7	1.8	1.3	-	1.2	1.0
4000	2.1	2.2	1.5	1.5	1.0	-
6000	2.8	2.5	1.7	1.6	-	-

*(Rose[11-18])

COLOR AND COLOR CONTRAST IN RESCUE EQUIPMENT

While color contrast is a factor to be reckoned with in the art of camouflage, most of the work in this field is due to the urgent need for adequate rescue equipment. The emphasis is on air-sea rescue, since quick detection is usually more important at sea than on land.

The comparative value of various colors has been worked out for smoke signals, flags, flares, parachutes, rafts, and markers of all sorts. The findings, of course, apply to missions other than search missions -- by choosing vivid markers to show where an enemy submarine was sighted, for example, and by choosing colors for ship-to-air signals. The various studies seem to agree that, except for smoke signals, red is the best color for signals that are to be seen from the air against sea backgrounds. The original color choice for air-sea rescue equipment was a bright yellow. This has been changed to a bright scarlet because it was observed that yellow life rafts blended with the bright reflection of the sun on the water.[11-4] The basis for the choice of bright red rests on such investigations as those done by two investigators in April 1944.[11-11] They found that a small red area retains its hue at a greater distance than any other color when the background is black or blue-green. White was next best under the same circumstances.

The effectiveness of yellow as compared with a graduated series of yellow-reds and reds was studied by another team.[11-15] Observations were made outdoors in sunlight at distances of fifty to one hundred and thirty feet from the targets. The test colors were 1/4-inch circles mounted on blue-gray boards representing the color of the sea under different weather conditions. The results indicated that yellow is a poor choice for life-saving equipment and that orange-reds of the same brightness are more visible. Others[11-19] extended this study by finding the relative threshold visibility of a series of light red-purples, reds, and yellow reds, unmodified by atmospheric attenuation. Colors within the range of real red proved more visible than other colors of the same brightness and chroma. The authors also point out that colors displayed against darker backgrounds were detected at much greater distances than when they were displayed against lighter backgrounds of similar contrast ratio.

For small objects such as flags, white should not be used, since it can be mistaken for whitecaps or foam.[11-2] The same criticism applies to yellow, which frequently appears white at a distance. Red is, again, the best color for pyrotechnics.

The minimum intensity of lights used in air-sea rescue must be a great deal higher in bad weather and during the day than on a clear night, if the lights are to be seen at any distance.[11-2] However, Table 11.3 shows that red is superior to other colors under a wide variety of atmospheric conditions. The table shows calculated minimum values at 5000 yards. Values at other ranges can be calculated by the inverse square law (Chapter 2).

Table 11.3 Candlepower Required for Light to be Seen at 5000 Yards[11-3]

Atmosphere Conditions	Red	Amber	White	Green
Night, clear	1.0	2.0	2.5	2.8
Night, light rain	1.2	2.1	3.0	3.2
Night, overcast and haze	3.2	4.1	3.1	5.9
Night, heavy rain	8.9	33.5	133.0	33.5
Night, light snow	222.0	835.0	1556.0	567.0
Day, overcast and haze	2000.0	2111.0	3222.0	4000.0
Day, clear	4778.0	7556.0	11,111.0	10,000.0

Marine smoke markers were tested during the day, under varying sky conditions, from a plane flying at 3000 feet.[11-1] A single observer flew on 51 test runs. For various colors, the range was found at which the smoke signal could no longer be identified as an artificial marker. The results indicated, in order of excellence: white, green, yellow, black, and blue. The superiority of white smoke was particularly marked under conditions of light wind, calm sea, mild weather, and good visibility. Apparently, white smoke markers produced a heavier flow of smoke than other markers and a column that rose straight up. The white smoke signal also persisted longer (about six minutes), indicating that perhaps it is not color alone that determines the choice for smoke markers. In any event, smokes that have a high contrast to the dark sea background are better than others.

There are fewer data on ground targets or signals to aid search, either (1) because sea search is more common, so color and color contrast values have been worked out more thoroughly, or (2) because earth backgrounds are more variable, so it is more difficult to specify one color as best for all conditions. What evidence we do have, however, again suggests the choice of reddish hues. In one study, six parachute canopies were tested for visibility against water, foliage, and sand from various altitudes. Each canopy was made up of alternating white and colored panels. Colors tested were international orange, fire orange fluorescent, and neon red fluorescent. Fire orange fluorescent was the most visible of the colors tested.

CAMOUFLAGE

Camouflage involves manipulating various attributes of the object one wishes to conceal. Concealment or deception is usually achieved by destroying the visual pattern (contour lines and texture) that makes it possible to detect an object against its background. Variations may be made in the color -- the hue, brightness, or saturation -- of the objects, so that it blends into the surrounding area; or characteristics of the surrounding area, such as foliage, may be superimposed on the target. For deceptive purposes, the aim may be to create a false impression of target characteristics or to create the illusion of a target where no target exists -- for example, to make it appear that there is a ground installation in the midst of a barren forest. Figure 11.1 shows an elaborate attempt at concealment and deception. In air-to-sea warfare, ships have been painted two-tone gray, mottled green, and dark gray to blend with the ocean. Often, camouflage need only be designed to conceal or deceive during a few crucial moments, as aircraft pass over an installation. In such cases, smoke screens or lights to dazzle may be used.

Figure 11.1 Labyrinth of Lines Has Been Painted on This Airstrip in an Attempt to Blend It With the Surroundings and to Confuse the Eye

At upper part of strip a road is simulated. Straight-line edges of the strip will stand out, however, and the light tone of the strip still contrasts with background. The terrain at left is used to conceal antiaircraft positions and aircraft revetments. Some revetments are covered.(Anon[11-5])

Complexity of Background

In the laboratory studies pertaining to visual air reconnaissance, two investigators[1-7] found that when certain critical targets were imbedded in a heterogeneous array of forms, the probability of picking out the correct target decreased linearly with the log number of forms in the array.* They also analyzed their data to find out how much the density of forms within a given area influenced visual performance. Surprisingly enough, their data showed no consistent effect of density or clustering upon recognizability of the target form. We do know, however, that, when objects are clustered together so that the contours of individual forms are obliterated or masked by overlapping, they are much harder to recognize.

Stationary vs. Moving Object

Whether an object moving on the sea or earth is easier to detect and identify from an aircraft than a stationary object probably depends on the task set for the observer. If his only function is to detect whether an object is present, a moving object is easier to detect, particularly against a heterogeneous background. Certainly, field tests tend to confirm this, even for low altitudes.[1-9] On the other hand, it is reasonable to suppose that identifying an object becomes more difficult as relative movement between the observer and the object increases. Other things being equal, angular relative movement between aircraft and ground objects increases as altitude decreases![1-14] Obviously there is room for more research in this area.

Number and Density of Objects

More data are also needed on how the number and density of objects affect their detectability.

In the visibility of light patches in low illumination, minimum perceptible brightness for scattered lighted areas is about the same as for a single area. This indicates that scattered lighting of a ground installation would not necessarily give it away. However, observers are better at detecting grouped objects than at detecting scattered objects.

Dispersing lighted areas at night and personnel by day are radically different. More data covering a wider variety of situations are required. It is likely that whether concentrating objects or scattering them is best depends on specific characteristics of object, atmosphere, and observer.

TECHNIQUE USED FOR DETECTION AND IDENTIFICATION

While some equipment and techniques vary with the mission, others are common to all missions involving air-to-ground vision. The effectiveness of navigation, bombing, reconnaissance, and search all depend in part on the speed and altitude of the aircraft, the search pattern, the scanning methods used, the length of the flight, and whether or not visual aids are used. These factors are discussed in the following paragraphs.

Speed and Altitude

Some have found that there are no significant differences in the ability of pilots to detect targets at quite widely different speeds during tactical aerial reconnaissance. Altitude is important. Above a certain altitude very few of the targets are recognized, and, when they are concealed, recognitions drop to nearly zero, even though the means of concealment are primitive. One study[11-13] gives the best search altitudes for day and night. Tactical reconnaissance pilots, who were interviewed, agree that low and slow flight is best for reconnaissance. On the other hand, high and fast flight is best for evasion. Where enemy defenses are

*This experiment is described above, under Size of Object.

good, reconnaissance pilots may be forced to perform at speeds and altitudes that make it impossible to do the careful searching required to spot camouflaged gun installations, well-deployed troops, and the like.

Search Patterns

Search plans set up for rescue operations are of the following main types: parallel sweeps, expanding square, and retiring square. Some information has been obtained[11-13] on search patterns in the course of testing the visual range of a variety of devices that might be used for emergency signalling from the surface of the ocean by day or night. Daytime plane runs were made in patrol bomber aircraft flying (1) head-on toward the signalling equipment with the sun at relative bearings of 0°, 315°, 270°, 225°, 180°, 135°, 90°, and 45°, and (2) on a "creeping line" search -- on parallel legs 8 to 15 miles long, working toward the equipment in 1-1/2-mile steps, starting 10 to 15 miles up-sun from the equipment. (Each leg was perpendicular to the sun's azimuth.) In head-on runs, the crew included a pilot, a co-pilot and two bow observers, one with binoculars, the other with polarized glasses. In creeping line runs, there were a pilot, co-pilot, two bow observers, and two waist observers, one with binoculars on a stick-mount, the other with binoculars on an anti-oscillation mount. As many observers looked down-sun as conditions allowed. Night observations were similar to day, with the moon instead of the sun used as reference. The investigators conclude that the best search track in clear daylight is a creeping line forward down-sun. On cloudy days and at night, an expanding square pattern is best; that is, the pilot flies a square pattern with increasingly longer legs, starting at the first estimated position of the object to be detected.

Visual reconnaissance techniques in the Air Force are based largely on collective experiences. The search patterns used actually seem very similar to those in search: a widening circle, which is like an expanding square, and a "plowing" pattern which is like a creeping line search. For reconnaissance along highways and the like, an S-curve is often flown. The main purpose of this pattern is to evade enemy fire, but it has the additional advantage that the pilot, being almost continuously in a bank, has a better downward view than in straight and level flight. Observer performance is increased by making a second pass over an area no matter what one's particular altitude. There is one very important point about reconnaissance in forested areas. That is that the observer must look straight down. A slanting sight line will locate only a small fraction or none at all of the targets depending on how heavily forested the area. This means that reconnaissance aircraft should be designed so that the observer can look straight down. Otherwise the pilot has to bank and turn the aircraft which means more time and vulnerability. It also discloses to the enemy that a reconnaissance has been made of the area, permitting him to move the targets before a target strike can take place.

Method of Scanning

Obviously, no search pattern will be effective unless the pilot or observer scans properly. That is, he must move his head and eyes in such a pattern that he does not miss large gaps of territory with his central vision (or his most efficient peripheral vision at night). He must scan at a slow, careful rate, but not so slow as to fly by objects in one sector while scanning another. Proper scanning pattern and rate vary with such factors as speed, altitude, time of day, object or target being hunted, and background. The following paragraphs summarize investigations into this problem.

Scanning procedures for larger aircraft are summed up as follows: Observers should be assigned for uniform coverage of the forward 180 degrees of azimuth, with an additional lookout in the tail to cover the aft position during the up-sun runs. Scanning should be carried out almost entirely along a line a few degrees below the horizon, with only short glimpses closer in. At heights up to 5000 feet, distances more than eight miles ahead are only a few degrees below the horizon. At 1000 feet, four miles away is only 2.5 degrees below the horizon on the clearest day. Since submarines, for instance, should be picked up at distances greater than four miles in average weather, it is essential to scan the sea just below the horizon. If too much time is spent scanning the sea within four miles of the plane, the average range at which submarines are sighted will be seriously reduced.

Scanning rates for small, dim targets were well investigated.[11-12] Targets were a series of eight silhouettes with three different contrasts and four different areas. Brightness levels varied from 1 to 10^{-4} millilamberts. Five enlisted men with lookout training served as subjects. They

were dark-adapted 45 minutes. One man placed a given target at a predetermined position. The second man recorded which target was presented, its position, brightness level, times at the beginning and end of scan, and time of discovery of the target. The third man scanned with 7 × 50 binoculars. A constant rate of scan was maintained with a metronome. The jobs were rotated every 30 minutes. Each man made 20 scans in his 30-minute observing period. Total scans per day were 320, total in the experiment, 6000. Scans alternated between fast and slow. For slow scanning, the metronome was set for ½ degrees every 8 seconds, and the subject was instructed to fix the horizon 0.5 degrees above the center of the field and to use some systematic pattern of search. For fast scanning, the metronome was set for 5 degrees every second; no specific instructions were given under this condition. It was found that, for very weak targets (low levels of illumination), the slower scanning rate gave shorter mean detection times. At higher levels of illumination, the faster scanning rate gave shorter mean detection times. In some situations, inconspicuous targets like rescue signals remain on the threshold of visibility for long periods. For example, for some time the aircraft may not close in on the target, so that it remains just visible if the observer looks right at it. In searching for such targets, slow scanning is proper. But in some pressing situations, fast scanning is definitely required.[11-12]

Duration of Flight

The shorter the flight that can accomplish the purpose, the better, since long uninterrupted flights mean high scanning fatigue.

SUMMARY OF AIR-TO-GROUND VISIBILITY PROBLEMS AND SOLUTIONS

Table 11.4 summarizes the problems in air-to-ground visibility and lists the methods of overcoming them. It can be seen from the table that in some cases the problem has not been examined systematically; that is why the spaces are left blank. Thus, the table can serve as a guide to areas requiring further investigation.

Table 11.4 Air-to-Ground Visibility: Summary of Problems and Solutions

	NAVIGATION	BOMBING	RECONNAISSANCE	SEARCH
A. Characteristics of the Observer				
1. Color vision	Must be good for reading of colored maps.	Must be good for differentiating ground targets.[11-18]	Must be good for same reasons as in bombing.[11-18]	Must be good for identifying colored signals.
2. Training	Observer can be trained to correlate terrain and map features.	Training in radar target recognition is desirable.	More and better training is needed.	Observers and pilots should learn to scan systematically and to report objects when they are not at all sure they are important.
3. Number of observers			Two men, alternating at the job.	Three to six (depending on field of view available).
B. Time of Day at Which Flight Occurs				
1. Best time	Midmorning to midafternoon			

Table 11.4 Air-to-Ground Visibility: Summary of Problems and Solutions (cont)

	NAVIGATION	BOMBING	RECONNAISSANCE	SEARCH
2. Night versus day		There is always more chance of seeing a suitable target marker at night than there is of seeing a natural aiming point by day.[11-21]	At night, full use should be made of moon's path. Down-moon, submarine should be picked up at 2 miles; up-moon, at 4 miles with naked eye.[11-6]	Night search from air for rafts without signals is practically hopeless.[11-13]
3. Poor atmospheric conditions				In overcast, orange smoke best and mirrors are ineffective.[11-13]
C. Characteristics of the Object Sought				
1. Size			Larger object easier to detect.	
2. Shape			Secondary variable in camouflage.	
3. Brightness contrast			Primary variable in camouflage.	
4. Color contrast				Red best for all signals except smoke markers.
5. Complexity of background			Objects are easier to detect against a simple background.	
D. Characteristics of the Technique Used				
1. Speed		The slower the better.		
2. Altitude		The lower the better.		
3. Search pattern			Parallel sweep or expanding circle or square.	
4. Scanning method			Just below the horizon, except in forested areas.	

Table 11.4 Air-to-Ground Visibility: Summary of Problems and Solutions (cont)

	NAVIGATION	BOMBING	RECONNAISSANCE	SEARCH
5. Aids	Use only for identification, not for detection.			
			Use cameras when full visual reconnaissance will not suffice.	
6. Duration of flight			The shorter the better.	
7. Special tricks			Look for tracks in desert and snow, trails that go off roads and stop, shadows, and angular formations in wooded areas.	

LIST OF REFERENCES

11-1 Anon. Great Britain, Air/Sea Warfare Development Unit, Report No. 48/3, NA London Ser. 0532 (B)-50. June 30, 1950. (CONFIDENTIAL)

11-2 Anon. The Comparative Visibility and Conspicuity of the Possible Colors for Air-Sea Rescue Equipment. Great Britain, Royal Air Force, Coastal Command, Operational Research Sect., ORS/CC Report No. 317. October 23, 1944.

11-3 Anon. Manuals in Pyrotechnics Visibility. USN, Air-Sea Rescue Agency, Bull No. 4. October 1944.

11-4 Anon. "Red Better than Yellow for Air-Sea Rescue Gear." Science News Letter. Vol. 62. No. 8. 1952.

11-5 Anon. Seeing from Aircraft: Training Notes for Naval Aviators and Aircrewmen. U. S. Navy, Aviation Training Div., Office of Chief of Naval Operations, Conavaer 00-805-59 OpNav 33-NY-72. July 1945.

11-6 Anon. Great Britain, Royal Air Force Coastal Command, Memo No. 50. February 12, 1943. (CONFIDENTIAL)

11-7 Boynton, R. M. and Bush, W. R., Laboratory Studies Pertaining to Visual Air Reconnaissance. WADC Tech. Report 55-304. Part I., Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. September 1955.

11-8 Chapanis, A., et al., USAF Contract 18(600)462. March 1953. (CONFIDENTIAL)

11-9 Dukes, E. F., Jr., and McEachern, L. J., WADC Tech Report 54-530, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. February 1955.

11-10 Duntley, S. Q., "The Visibility of Distant Objects." J. Opt. Soc. Amer. Vol. 38. March 1948. pp. 237-249.

11-11 Farnsworth, D., and Reed, J. D., Preliminary Report USN Submarine Base, Medical Research Laboratory, Color Vision Report No. 7. April 20, 1944. (CONFIDENTIAL)

11-12 Kimball, G., Min. 13th, Meet. Vision Committee. July 10-11, 1945. pp. 25-33.

11-13 Leavitt, D. F., USN, BuAer, Prel. Report on TED No. UML 25159. May 6, 1945.

11-14 Ludvigh, E. J., The Influence of Dynamic Visual Acuity on the Visibility of Stationary Objects Viewed from an Airfract Flying at Constant Altitude, Velocity, and Direction. Report 3, Kresge Eye Inst., Detroit, Mich. October 1953.

11-15 Malone, F. L., Sexton, M. S., and Farnsworth, D., The Detectability of Yellows, Yellow-Reds, and Reds in Air-Sea Rescue. USN Submarine Base, Medical Research Laboratory Report No. 182, BuMed. & Surg., Navy Dept. Project NM 003 041.35.01., New London, Conn. Vol. 10. 1951. pp. 177-185.

11-16 Matthews, J. C., An Investigation of Certain Aspects of Color Vision. USAF School of Aviat. Med., Project No. 168, Report 1, Randolph Field, Texas. August 4, 1943.

11-17 Meetham, A. R. and Lambert, G. E. V., Great Britain, Ministry of Home Security, CDRC, Subcommittee g (Photometric properties of atmosphere), R. C. (G) 3. December 24, 1941. (CONFIDENTIAL)

11-18 Rose, D. C., BuMed. & Surg., AORG, Report 22., Canada. February 27, 1945. (CONFIDENTIAL)

11-19 Sexton, M. S., et al., The Relative Detectability of Red-Purples, Reds and Yellow-Reds in Air-Sea Rescue. USN, Submarine Base, Medical Research Laboratory Report No. 195, Vol. 11. No. 12. New London, Conn. March 19, 1952.

11-20 Wallace, S. R., et al, USAF Train. Command Psychol. Sect. Research Bull. Hq. 43-6. October 14, 1943.

11-21 Walters, D. J., Great Britain, Royal Aircraft Est., Farnborough, England. April 1951.

GENERAL BIBLIOGRAPHY

11-22 Anon. Great Britain, Royal Air Force, Coastal Command, Operational Research Sect. Report No. 245. August 13, 1943.

11-23 Anon. The Application of Color to Shore Establishment. U. S. Navy Dept. Bureau of Yards and Docks, Washington, D. C. 1953.

11-24 Anon. Approach Angle Light and Collateral Equipment for Helicopter Landing Areas. Naval Air Test Center, Patuxent River, Md. September 1953.

11-25 Anon. Blackout of Buildings. U. S. Office of Civilian Defense Publication No. 3047. 1949.

11-26 Anon. Camouflage, Basic Principles. U. S. Army Field Manual FM 5-20. June 1, 1940.

11-27 Anon. U. S. Office of Scientific Research and Development, National Defense Research Committee, OSRD No. 5371, Pratt, Read and Company, Inc., Deep River, Conn. August 31, 1945. (CONFIDENTIAL)

11-28 Anon. U. S. Office of Scientific Research and Development, National Defense Research Committee, OSRD No. [illegible], Tiffany Foundation, [illegible] June 1, [illegible]. (CONFIDENTIAL)

11-29 Anon. Great Britain, Royal Air Force, Coastal Command, Operational Research Sect. Report No. 259. November 8, 1943.

11-30 Anon. Factors Affecting Night Visibility. Great Britain, Royal Air Force Middle East Forces, Air Tactical Hq., Tech. Memo No. 11. March 1942.

11-31 Anon. Final Report on Project No. APG/TAT/121-A, ASTIA Ad-41 368. USAF, Air Proving Ground Command, Elgin Air Force Base, Fla.

11-32 Anon. Identification Ranges for Colored Light Signals. U. S. Navy Bureau of Ships, Electrical Sect. Report No. 5. 1944.

11-33 Anon. Optionic Instruments for the Study of Camouflage. Interchemical Corporation, Research Laboratories. OSRD No. 6556. August 25, 1945.

11-34 Anon. Precautionary Camouflage, A Guide for Promiting Low Visibility Principles without Dependence upon Artificial Coverings. U. S. Office of Civilian Defense Publication No. 2019. September 1943.

11-35 Anon. Protective Concealment. U. S. Office of Civilian Defense. March 1942.

11-36 Anon. Reflectance of Natural Terrains. U. S. Office of Scientific Research and Development, National Defense Research Committee. OSRD No. 6554. Tiffany Foundation. September 14, 1945.

11-37 Anon. Great Britain, Royal Air Force Coastal Command, Operational Research Sect. Report 208. No. WA-5675-1A.

11-38 Anon. Visual Reconnaissance from Aircraft. U. S. Navy BuAer Report No. 00-80T-45 NAVAER 00-80T-45. 1953.

11-39 Anon. Great Britain, Royal Air Force Coastal Command, Operational Research Sect. Report No. 283. April 3, 1944. (CONFIDENTIAL)

11-40 Anon. U. S. Office of Scientific Research and Development, National Defense Research Committee. OSRD No. 6401 Report 7. Tiffany Foundation. October 1, 1945.

11-41 Archer, J. E., "Identification of Visual Patterns as a Function of Information Load." J. Exp. Psychol. Vol. 48. 1954. pp. 313-317.

11-42 Arnoult, M. D., "Shape Discrimination as a Function of the Angular Orientation of the Stimuli." J. Exp. Psychol. Vol. 47. 1954. pp. 323-328.

11-43 Arnoult, M. D., "Transfer of Predifferentiation Training in Simple and Multiple Shape Discrimination." J. Exp. Psychol. Vol. 45. 1953. pp. 401-409. Research Bull. 53-48. HRRC, Perceptual and Motor Skills Research Laboratory, Air Research and Development Command, Lackland Air Force Base, Texas.

11-44 Austin, G. A., The Effect of Stimulus Area on Visual Intensity Threshold. 1951.

11-45 Beck, L. H., Appropriate Units for Describing Visibility Data. University of Michigan, Vision Research Laboratory, Optics and Vision Group. July 1, 1955.

11-46 Beverly, R. F., and Kausler, D. H., The Effect of Practice on Circular Error and Its Components in Visual Bombing. HRRC, Aircraft Observer Train. Research Laboratory, Air Training Command, Mather Air Force Base, Calif. February 1952.

11-47 Bouman, M. A., and Blockhuis, E. W. M., "The Visibility of Black Objects Against an Illuminated Background." J. Opt. Soc. Amer. Vol. 42. 1952. pp. 525-528.

11-48 Brackett, F. S., Visual Requirements for Spotting. U. S. Army Service Forces, Armored Medical Research Laboratory, Project No. 6, Sub. Project No. 6-1, 6-6. Ft. Knox, Ky. February 20, 1943.

11-49 Bricker, P. D., "The Identification of Redundant Stimulus Patterns." J. Exp. Psychol. Vol. 49. February 1955. pp. 73-81.

11-50 Bridgman, C. S., and Wade, E. A., Sensitivity to Changes in Stimulus Size Reaction Time as a Function of Rate of Change. Tech. Report 53-199, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. April 1953.

11-51 Brown, E. L., Matheny, W. G., and Glexman, R. E., Evaluation of the School Link as an Aid in Teaching Ground Reference Maneuvers. TR SDC 71-16-7 SDC Human Engineering Project 20-L-1, NR-784-003, University of Ill. December 1950.

11-52 Brown, G. E., Jr., Generality of Tracking Training. U. S. Office of Science Research and Development, National Defense Research Committee, OSRD No. 4508, Tufts College. December 28, 1944.

11-53 Burnahm, R. W., Newhall, Sidney M., "Color Perception in Small Test Fields." J. Opt. Soc. Amer. Vol. 43. October 1953. pp. 894-902.

11-54 Burton, A. C., Great Britain, OSRD No. III-I-2244, Proc. 12th Meeting. September 30, 1943. pp. 45-46. (CONFIDENTIAL)

11-55 Burton, A. C., and Bright, H. J., Great Britain, OSRD No. III-I-2227, A.C.A.M.R. Report No. C2567 Subcommittee on Protective Clothing Report No. 143. August 30, 1943.

11-56 Burton, A. C., and Emery J. N., Great Britain, OSRD No. III-I-2228, C2527 Subcommittee Protective Clothing Report No. 133. June 28, 1943.

11-57 Carpenter, A., A Study of the Involuntary Blink Rate During Prolonged Visual Search. Great Britain, Medical Research Council, Applied Psychology Research Unit, A.P.U. 21, Psychological Laboratory, MRC 48/49, Cambridge, Mass. July 1945.

11-58 Casperson, R. C., "The Visual Discrimination of Geometric Forms." J. Exp. Psychol. Vol. 40. October 1950. pp. 668-681.

11-59 Cheatham, P. G., "Visual Perceptual Latency as a Function of Stimulus Brightness and Contour Shape." J. Exp. Psychol. Vol. 43. No. 5. May 1952. pp. 369-380.

11-60 Christensen, J. M., and Crannell, C. W., The Effect of Selected Visual Training Procedures on the Visual Form Field. WADC Tech. Report 54-239, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. April 1955.

11-61 Clark, W. C., Smith, A. H., and Rabe, A., "The Interaction of Surface Texture Outline Gradient, and Ground in the Perception of Slant." Canadian J. Psychol. Vol. 10. 1956. pp. 1-8.

11-62 Clark, W. C., Smith, A. H., and Rabe, A., "Retinal Gradient of Outline as a Stimulus for Slant." Canadian J. Psychol. Vol. 9. 1955. pp. 247-253.

11-63 Craik, K. J. W., Filters for Anti-Glare Goggles, With Special Reference to Observation from Aircraft. Great Britain, Psychological Laboratory, OSRD No. WA-3499-2a. Cambridge University. July 24, 1943.

11-64 Craik, K. J. W., and Macpherson, S. J., Naked Eye Scanning by Day, with Special Reference to Observation from Coastal Command Aircraft. Great Britain, Psychological Laboratory, Cambridge University.

11-65 Cross, H. F., Project TED No. PTR-2553, U. S. Naval Air Station, Patuxent River, Md. September 1, 1944. (CONFIDENTIAL)

11-66 DeAngelis, Q. C., Winter Arctic Camouflage Investigation. Project 8-31-03-004, Report 1334, Engineer Research and Development Laboratories, Fort Belvoir, Va. December 1953.

11-67 Deese, J., Complexity of Contour in the Recognition of Visual Form. Tech. Report 56-60, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. February 1956.

11-68 Deese, J., and Ormond, E., Studies of Detectability During Continuous Visual Search. Tech. Report 53-8, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. September 1953.

11-69 Doidge, W. T., and Holtzman, W. H., Influence of Color on Form Perception. American Psychological Association, Cleveland, Ohio.

11-70 Duntley, S. Q., The Visibility of Submerged Objects: Final Report. Visibility Laboratory, Massachusetts Institute of Technology, Office of Naval Research, Bureau of Ships. August 31, 1952.

11-71 Elkind, J. I., Tracking Response Characteristics of the Human Operator. Human Factors Operations Research Laboratory Memo. No. 40, PRP-2, Air Research and Development Command, Bolling Air Force Base, Wash. September 1953.

11-72 Eriksen, C. W., Partitioning and Saturation of the Perceptual Field and Efficiency of Visual Search. WADC Tech. Report 54-161, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. April 1954.

11-73 Farnsworth, D., Proposed Specifications of Red and Green Navy Signal Lights. Medical Research Laboratory Report No. 115, Color Vision Report No. 16, USN Submarine Base, New London, Conn. October 6, 1947.

11-74 Fleishman, E. A., and Hempel, W. E., Jr., "The Relation Between Abilities and Improvement with Practice in a Visual Discrimination Reaction Task." J. Exp. Psychol. Vol. 49. 1955. pp. 301-312.

11-75 Garrett, S. E., and Cross, H. F., "Camouflage." Project TED No. PTR-2556, U. S. Naval Air Station, Patuxent River, Md. May 14, 1945.

11-76 Gibson, E. J., A Survey on Improvement in Perceptual Judgments as a Function of Controlled Practice and Training. Human Resources Research Center, Research Bull. 53-45, m Project 509-019-0003, Air Research and Development Command, Lackland Air Force Base, Texas. November 1953.

11-77 Gibson, E. J., Bergman, R., and Purdy, J., "The Effect of Prior Training with a Scale of Distance on Absolute and Relative Judgments of Distance over Ground." J. Exp. Psychol. Vol. 50. August 1955. pp. 97-105.

11-78 Graham, C. H., Visual Intensity Discrimination. U. S. Navy, Office of Naval Research, Monthly Research Report 17-20, Project NR142-404, Contract N6onr-271, Task Order IX, Columbia University. March 1950.

11-79 Halsey, R. M., and Chapanis, A., "Chromaticity-Confusion Contours in a Complex Viewing Situation." J. Opt. Soc. Amer. Vol. 44. 1954. pp. 442-454.

11-80 Hamilton, C. E., Preliminary Study of the Effects of Training Upon Observer Capacity. Research Report No. 6, Optics and Vision Group, Research Laboratories, University of Michigan. June 2, 1955.

11-81 Hartridge, H., "Chromatic Aberration and the Polychromatic Theory." Brit. Med. Bull. Vol. 9. No. 1. 1953. pp. 31-36.

11-82 Holston, R. P., Some Effects of Motivation on Visual Discrimination. 1950.

11-83 Holway, A. H., and Boring, E. G., "The Dependence of Apparent Visual Size Upon Illumination." Amer. J. Psychol. Vol. 53. 1940. pp. 587-589.

11-84 Imber, B. M., Stern, I. D., and Vanderplas, J. M., Visual Field Restriction and Apparent Size of Distant Objects. WADC Tech. Report 54-23, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. January 1954.

11-85 Kincaid, W. M., and Hamilton, C. E., Preliminary Studies of the Influence of Knowledge of Target Magnitude upon Detection Probability. University of Michigan Vision Research Laboratory, Optics and Vision Group, Project W2144-805-M, Research Report 10. June 22, 1955.

11-86 King, H. E., Carney, L., and Zubin, J., "Visual Subliminal Perception Where a Figure is Obscured by the Illumination of the Ground." J. Exp. Psychol. Vol. 34. 1944. pp. 60-69.

11-87 Kristofferson, A. B., Preliminary Study of Detection Thresholds for Discontinuous Targets: I. Target Known Exactly. University of Michigan Vision Research Laboratory, Optics and Vision Group, Project No. 2144-816-M, Research Report 12. July 1, 1955.

11-88 Lamar, E. S., Hecht, S., Hendley, C. D., and Shlaer, S., "Size, Shape, and Contrast in Detection of Targets by Daylight Vision." J. Opt. Soc. Amer. Vol. 38. No. 9. September 1948. pp. 174-755.

11-89 Lamar, E. S., Hecht, S., Shlaer, S., and Hendley, C. D.,"Size, Shape, and Contrast in the Daytime Detection of Targets." J. Opt Soc. Amer. Vol. 36. 1946.

11-90 Levens, Alexander S., Nomography. 1937.

11-91 Livingston, P.C., Report on Some Visual Problems of Submarine Detection. Great Britain, Flying Personnel Research Committee Report No. 346, OSRD Liaison Office Ref. No. WAM-67-2. August 1941.

11-92 Low, F. N., "Effect of Suprathreshold Changes in Brightness on Form Perception." Amer. J. Physiol. Vol. 155. 1948. pp. 409-419.

11-93 MacDonald, D. E., and Dillor, R. E., A Collection of Graphs Concerning Atmospheric Transmission, Natural Illumination and Reflectance of Terrain. Tech. Note. No. 87, Optical Research Laboratory, Boston University. July 1952.

11-94 Mackworth, N. H., "The Breakdown of Vigilance During Prolonged Visual Search." Quart. J. Exp. Physiol. Vol. 1. Part I. April 1948. pp. 6-21.

11-95 Malone, F. L., A Preliminary Field Evaluation of the Relative Detectability of Colors for Air-Sea Rescue. No. 22, Report No. 237,Medical Research Laboratory, USN Submarine Base, New London, Conn. November 23, 1953.

11-96 Middleton, W. E. K., "A Study of the Conspicuity of Orange Surface Colors." Illum. Engng. Vol. 47. February 1952. pp. 95-98.

11-97 Middleton, W. E. K., and Holmes, M. C., "The Apparent Colors of Surfaces of Small Subtense." J. Opt. Soc. Amer. Vol. 39. 1949. pp. 582-592.

11-98 Minturn, A. L., Reese, T. W., and Kaufman, E. L., The Effect of a Simple Training Procedure on the Judgment of Visual Number. Special Devices Center Report 131-I-1, Mt. Holyoke College. September 1951.

11-99 Moeller, G., Fooks, G., Sperling, H. G., Farnsworth, D., and Wendt, H. W., Evaluation of Optical Filters for Special Military Purposes. I. Dark Adaptation and the Near Ultraviolet. II. Evaluation of an Experimental Air-Sea Rescue Goggle. Contract Nonr 1276(00), Project NR 142-082, Final Tech. Report,ONP, Conn. College. February 1956.

11-100 Nachman, M., The Influence Size and Shape on the Visual Threshold of the Detectability of Targets. Contract AF 33(616)432, Tech. Note No. 109, Boston University, Optical Research Laboratory, Boston University. December 1953.

11-101 Niven, J. I., and Brown, R. H., "Visual Resolution as a Function of Intensity and Exposure Time in the Human Fovea." J. Opt. Soc. Amer. Vol. 34. 1944. pp. 738-743.

11-102 Oldfield, R. C., Visual Search for an Inconspicuous Object. FPRC 681. MRC, Flying Personnel Research Committee, Psychological Laboratory, Cambridge, England. March 1947.

11-103 Ogle, K. N., "On Stereoscopic Depth Perception." J. Exp. Psychol. Vol. 48. No. 4. 1954.

11-104 Platzer, H. L., A Non-Linear Approach to Human Tracking. Franklin Institute Laboratories for Research and Development, Interim Tech. Report I-2490-1. 1955.

GENERAL BIBLIOGRAPHY (Cont)

11-105 Rowland, Louise S., Selection and Validation of Tests for Color Vision. A Test for Ability to Distinguish Terrain Colors. Project No. 137, Report No. 3, U. S. Air Force School of Aviat. Med., Randolph Field, Texas. May 31, 1943.

11-106 Rowland, Louise Sloan, and McDonald, Phillip R., Selection and Validation of Tests for Color Vision---The Recognition of Pyrotechnic Signals by Normal and Color Deficient Subjects. Project No. 137, Report No. 5, U. S. Air Force School of Aviat. Med., Randolph Field, Texas. November 1, 1943.

11-107 Smith, Stanley W., Preliminary Studies of the Relation Between Target Size and Detectibility at Low Background Luminance. University of Michigan Vision Research Laboratories, Optics and Vision Group, Project No. 2144-825-M, Research Report 19. July 8, 1955.

11-108 Swets, John A., An Experimental Comparison of Two Theories of Visual Detection. 1954.

11-109 Swets, J. A., Tanner, W. P. Jr., and Birdsall, T. C., The Evidence for a Decision-Making Theory of Visual Detection. Engineering Research Institute, University of Michigan, Electronic Defense Group, Tech. Report No. 40. March 1955.

11-110 Tanner, Wilson P. Jr., and Swets, John A., "A Decision-Making Theory of Visual Detection." Psychol. Rev. Vol. 61. No. 6. 1954. pp. 401-409.

11-111 Taylor, G. G., "Theoretical and Practical Aspects of Fluorescence, Luminescence, and Phosphorescence." J. Soc. Dyers and Colourists. Vol. 66. 1950. pp. 181-186.

11-112 Terrell, Claude M., Army-Navy-OSRD Vision Committee, Minutes and Proceedings of the Fourth Meeting. July 27, 1944. pp. 31-37. (CONFIDENTIAL)

11-113 Verplanck, Wm. S., Final Report: Response Mechanisms at the Visual Threshold - A Methodological Study. Office of Naval Research, Project NR140-253, Indiana University. July 10, 1952.

11-114 Wever, Ernest Glen, "Figure and Ground in the Visual Perception of Form." Amer J. Psychol. Vol. 38. pp. 194-226.

11-115 Whittingham, D. G. V., and Ellis, W. H. B., Conspicuity of Coloured Fluorescent Fabrics for Air-Sea Rescue. Flying Personnel Research Committee No. 844, Code No. 2021, NRL Document No. 118 865, Naval Research Laboratory, Washington 25, D. C. August 1953.

11-116 Witkin, H. A., "Individual Differences in Ease of Perception of Embedded Figures." J. Personality. Vol. 19. No. 1. September 1950. pp. 1-15.

11-117 Wyckoff, L. B., Bridgman, C. S., and Tabory, L., The Effect of an Improved Orientation Aid on Target Acquisition with the Hemispheric Sight. WADC Tech. Report 54-67. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. January 1954.

CHAPTER 12

TAKE-OFFS AND LANDINGS

This chapter deals with the visual problems that arise during take-offs and landings and the factors that influence visual performance in these flight phases. First, research on problems arising at the time of airport arrival are discussed - i.e., dealing with the traffic pattern and making appropriate distance and movement judgments. Then, approach and touchdown difficulties are enumerated. Visual aids such as runway and approach lights and runway markings constitute the next part of the chapter and taxiing is discussed at the end of the chapter.

THE IMPORTANCE OF VISION DURING TAKE-OFF AND LANDING

On the basis of many analyses, we know that a large percentage of aircraft accidents are blamed on human error. Poor or inaccurate visual judgments often play a major role, though not necessarily the only role, in the series of events which lead to an accident.

In some analyses of aircraft accidents, a few of the visual causes have been isolated. Researchers[12-35] studied accidents caused by over- or under-shooting the runway in non-emergency landings. They state that "... the primary cause [of under- or over-shooting] was faulty distance-rate-of-closure judgment on the part of the pilot." They go on to point out that "... factors which reduced visibility or interfered with normal depth perception resulted in an increased frequency of these types of accidents." They suggest that such accidents could be reduced by visual glide path indicators and clearly marked touchdown areas.

Another study[12-10] showed that errors in visual performance were repeatedly among the errors leading to jet aircraft accidents. The single most important visual problem was the pilot's failure, for one reason or another, to see collision objects. This study brought out that most of the factors affecting visual performance were contributing causes of one or more accidents.

VISUAL RESEARCH RELATED TO TAKE-OFF AND LANDING

Airport Arrival

Several visual cues help a pilot discriminate a runway from the surrounding terrain which serves as background. Important ones are brightness contrast, color contrast, and texture differences. At a distance, brightness contrast seems to be more important than the others; the colors lose their purity, so that color contrast is below threshold, and the microstructure of runway and terrain, which supplies the texture differences, cannot be discriminated. As one approaches the airport, color contrast and texture become increasingly effective and tend to reinforce the brightness contrast cues.

In one study[12-12], brightness contrast measurements between runway surfaces and surrounding terrain were made at sample airports. It was found that in many cases the contrasts obtained were below a value of 0.05, which is the commonly accepted threshold for contrast. An asphalt runway viewed against a grass background yielded a contrast value of .045, which was below threshold. White concrete runways viewed against an earth background were the best, with a contrast value of -1.175; but even this was not far above threshold.*

*Contrast is $\frac{\Delta B}{B}$, where B is the brightness of the background and ΔB the difference between the brightness of the object (in this case, the runway) and the background. A negative contrast value means that the object is brighter than the background. In the case of an airport runway, one is interested in the apparent contrast -- the contrast as seen from a distance, where the brightness of runway and terrain are affected by atmospheric attenuation (see Chapter 9). The minimum contrast that can be discriminated decreases as the absolute brightness increases (see Fig. 8.12, Chapter 8); contrast below threshold on a dull day may be above threshold on a clear, sunny day.

When visibility estimates are made to determine whether visual flight rules shall apply, they are made on the basis of objects that contrast well with their backgrounds. Thus, when one-mile visibility is reported, a pilot may not be able to distinguish a runway until he is much closer than a mile, if the runway has a low contrast with its background. A series of theoretical curves[12-12] shows how far out a pilot can distinguish a runway at various values of reported visibility. One of these curves is presented in Figure 12.1. This figure shows when visibility was estimated at one mile that even concrete against earth (contrast = -1.75) could not be seen until the aircraft has approached to within a half mile.

Because of the shape of the curves like that in Figure 12.1, large improvements in runway visibility can be made by small improvements in contrast when the initial contrast is low. The above study[12-12] concludes that for a majority of the airports studied the contrast between runway and background was in the range where a large increase in runway visibility could be accomplished by a relatively small improvement in contrast.

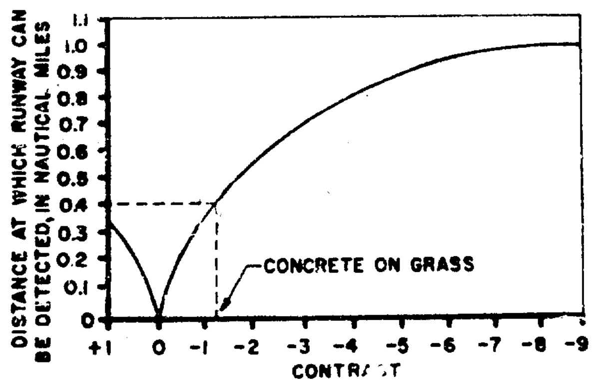


Figure 12.1 Calculated Distances at Which Runway can be Detected at Various Contrasts When Visibility is Estimated at One Mile on the Basis of Meteorological Conditions (after Barr, Hussman, and Parker[12-12])

Pilots often do approach the runway properly when brightness contrast, color contrast, and texture difference are below threshold; the obvious question is what does the pilot use as a guide under such circumstances? A definitive answer cannot be given. However, it seems likely that major features of the terrain are used up to the point where the runway becomes visible. Form perception may play a role in this process. For example, it has been suggested that angular shapes of man-made objects, such as airport boundaries and hangars, can be distinguished from the irregular forms of nature.

The Traffic Pattern

When flying in the traffic pattern established for an airport, the pilot must make a continuous series of several kinds of visual judgments.

Distance judgments (i.e., depth perceptions) are probably the most important; they include judgments of both relative and absolute distance. The pilot must judge how far he is from other airplanes, which of two planes is most distant, how high he is above ground obstacles, and how far he is from various points on the airport. On the basis of this series of judgments he forms a perception of three-dimensional space in which he locates himself and all the other important objects in his environment. Anything that influences the accuracy of his depth judgments thus affects the precision and safety of flight in the traffic pattern.

The pilot must also continuously judge both relative and absolute motion -- the relative motion of the ground as well as the relative and absolute motion of other aircraft. On the basis of these judgments the pilot adjusts his position to fit in with other traffic or to avoid collisions,

and is reminded to maintain his proper airspeed (checked by the airspeed indicator). Depth and motion judgments are of course related (see Chapter 8).

Distance Judgment

Background brightness has been found[13-14] to influence the accuracy of both depth judgments and ability to judge whether objects are aligned (vernier discriminations). Investigators conclude that judgment of real depth is more influenced by brightness changes than are vernier discriminations. There is a curvilinear relation between background brightness and accuracy in both kinds of discrimination. The critical value falls at about one millilambert; above it, practically no improvement in accuracy takes place. They also conclude that at low levels of background brightness, visual acuity seems to be the important factor in judging depth or alignment, but at higher levels such judgments are based on differences in brightness, etc., between objects and background. These results were obtained for judgments of relative depth. It would be interesting to see where they also apply to judgments of absolute depth (i.e., ability to estimate the actual distance of an object).

These findings indicate that the distance of another aircraft will be more accurate when it is viewed against the sky than when it is viewed against the relatively dark ground. They also indicate that the judgments may be based on different types of visual performance. Other aircraft being observed in a traffic pattern often pass from one of these backgrounds to the other. Each change in background presumably raises or lowers the accuracy with which their distance may be judged. This could account for some of the difficulties in judging and maintaining proper spacing in flight patterns.

Judging Motion. The detection of motion has been systematically explored. Many variables influence the threshold velocity -- the lowest velocity an object can have and be seen as moving. These include the direction of movement, duration of observation, illumination, size of the field against which the object moves, the retinal area stimulated, and the type of background. As has been pointed out, the detection of motion is important in flying in a restricted air space, such as a traffic pattern, with other aircraft. For example, one way to avoid collision is to observe whether other aircraft are moving relative to the observer. If no motion is detected and the oncoming aircraft is getting larger, it is on a collision course with the observer. Any of the variables that influence motion detection thus affect the pilot's ability to judge whether he is on a collision course with another aircraft. Motion of an object in relation to a variegated background (differential movement of images on the retina) is most readily detected.

The flight situation calls for such motion discriminations to be made against moving backgrounds over a wide range of speeds. Adding to the complexity of this problem, eyes are also moving. Thus, judgments of relative motion and acceleration are by no means simple; the target, the background, the observer, and the eyes are all in motion at the same time. Nevertheless, judgments of motion are made successfully by people who fly airplanes. The presentation of a few of the issues and findings should serve to make the problem a little clearer.

One study[13-21] examines two possible explanations of how the eye detects motion against a homogeneous background. One is that the eyes follow a moving object so that it remains fixated on the fovea. The cues of movement are supplied by the eye muscles; in some way the brain works head movements into the "equation." The other explanation is that while the eye fixates the object, the background images must flow across the retina in unique patterns that bear a direct relation to the depth, rate, and direction of

motion of the target. These "flow" patterns are thus assumed to provide the cues for our judgments.

Related to the problems presented by moving targets and backgrounds is the effect of motion on visual acuity. The ability to discriminate visual detail while following an object with the eyes is sometimes called dynamic visual acuity. It has been found[12-1, 12-3] that individuals with substantially the same static acuity* may differ greatly in dynamic acuity. This means that the tests of visual acuity usually used in selecting pilots may be poor for predicting their ability to discriminate visual detail in take-off, landing, and other situations that require the pilot to track objects moving at high relative angular velocities. A test of dynamic acuity might be desirable in establishing visual standards for pilots. Many of the differences in dynamic visual acuity probably may be due to differences in tracking efficiency.

Visual vs. Other Cues in Approach. Aside from information furnished by instruments, the pilot has three types of cues to tell him whether he is departing from his correct glide path. They are: (1) visual cues, such as those described in the foregoing paragraphs; (2) cues furnished by the response of sense organs in the vestibule of the ear to accelerations including the pull of gravity; and (3) cues furnished by tension and movement of muscles and other tissues within the body. (The last two types of cues are those that enable a man to sense whether he is moving, maintaining balance, etc., even in the dark.)

Though flight instruments give the most precise and probably the quickest indication of departures from the flight path, because they amplify aircraft movements and give more definite points of reference, judgments can be made well on the basis of the three classes of cues given above. Numerous studies[12-[illegible], 12-[illegible], 12-[illegible]] have shown the superiority of visual cues over the others for detecting movement or rotation of the body. A wide and clear visual field that permits the operation of these visual cues is important for this reason as well as for many others.

Conclusions. Only very general conclusions can be drawn from available research on the visual problems involved in flying at low elevation in the traffic pattern. First, the visual judgments concerning depth, movement, and shape seem to be the important ones. Second, these judgments depend to some extent on one another; for example, judgment of relative motion depends partly on judgment of depth, and vice versa. Third, the variables that affect these visual judgments are continuously interacting, so that the accuracy of a series of depth judgments is changing continuously. On the other hand, visual research workers have tended to analyze the effect of one variable at a time on one kind of visual performance; obviously, their data can solve only a small portion of the operational visual problems. It seems that more visual research should be conducted with the actual conditions of flight in mind.

Final Approach and Touchdown

The importance of vision in this critical final phase of flight is obvious. However, the part played by each type of visual performance and the effects of the many visual variables remain largely unevaluated. According to one survey team[12-[illegible]] "...after 60 years of powered flight there is no accepted theory on the means of making visual

* i.e., the ability to discriminate stationary objects.

judgments about the progress of an approach to landing, or orthodox training in this task...." They name certain cues that they feel are important in landing. They suggest that these cues could be fed into a landing simulator suitable for research and training in landing techniques. Other investigators[12-13, 12-18] also advise building simulators to gain a greater understanding of the visual and psychological processes that take place during landing.

Eye Movements During Landing. To study the problem in actual landing operations, the pilot's eye movements have been recorded during landing. Photographs showing the position of the pilot's eyes during landing were analyzed to find out what he was looking at. They showed that the pilot was looking out of the cockpit only about 50 percent of the time.[12-17] The rest of his time he spent looking in the cockpit or shifting his eyes between the cockpit and outside. The chief reason for looking in the cockpit was to read the airspeed indicator; when airspeed information was fed into the pilot's ears, his eyes spent nearly 100 percent of the time outside the cockpit. This suggests that landing would be greatly improved if airspeed information were given to the pilot so that he did not have to take his eyes off the runway.

In another study,[12-31] researchers took motion pictures of eye movements during the last five to ten seconds before touchdown. They compared groups of experienced and inexperienced pilots but could find no clear cut differences between the characteristic movements of the two groups. In general, both groups moved their eyes back and forth horizontally before fixating a point straight ahead. More data on eye movements, and instrument arrangements based on these data, are described in Chapter 19.

Other researchers[12-16] made photographic records of eye movements during standard flight maneuvers. The pilots were experienced airline pilots. In general, they found that the range of eye movements is less during take-off and landing than at other times; during these phases of flight, most eye movements fall within a cone of approximately 80 degrees, and the largest amount of time is spent looking straight ahead. Their data suggest that the most compelling problem during landing is keeping the aircraft lined up with the runway. Maintaining proper attitude with reference to the distance above the runway is a correlated problem. How the pilot is able to judge his height above the runway or the rate of sink of his aircraft becomes a matter of conjecture. One explanation is as follows:

Expanding Visual Patterns During Landing. In landing, the images of various objects in the visual field expand and flow toward the periphery of the retina as the objects are approached and passed. This results as a function of a multitude of motion parallaxes. One reporter[12-21] suggests that this expanding pattern enables the pilot to judge his position in space and his rate of descent. In analysis, there is a zero point in the expansion pattern from which all movement radiates. It is the point at which the aircraft is flying. As the aircraft comes closer to touchdown, the zero point of the expansion pattern moves to a new location. Figure 12.2 shows a schematic representation of the expansion patterns associated with approaches for landings. In Figure 12.2, the zero point is located at the expected point of touchdown. The data on eye movements seem to indicate that the pilot during landing is largely occupied with watching this zero point in the expansion pattern. Since he never looks at the runway under him, he must judge his height (1) from perspective and (2) from differences in apparent movement (movement gradients) in the expansion pattern -- including the portions of the pattern in the periphery of the visual field. For example, the apparent movement of the ground under the aircraft (or as nearly under it as the pilot can see) relative to the surrounding land is a function of his height, and the rate of increase in this relative apparent movement is a function of his rate of descent.

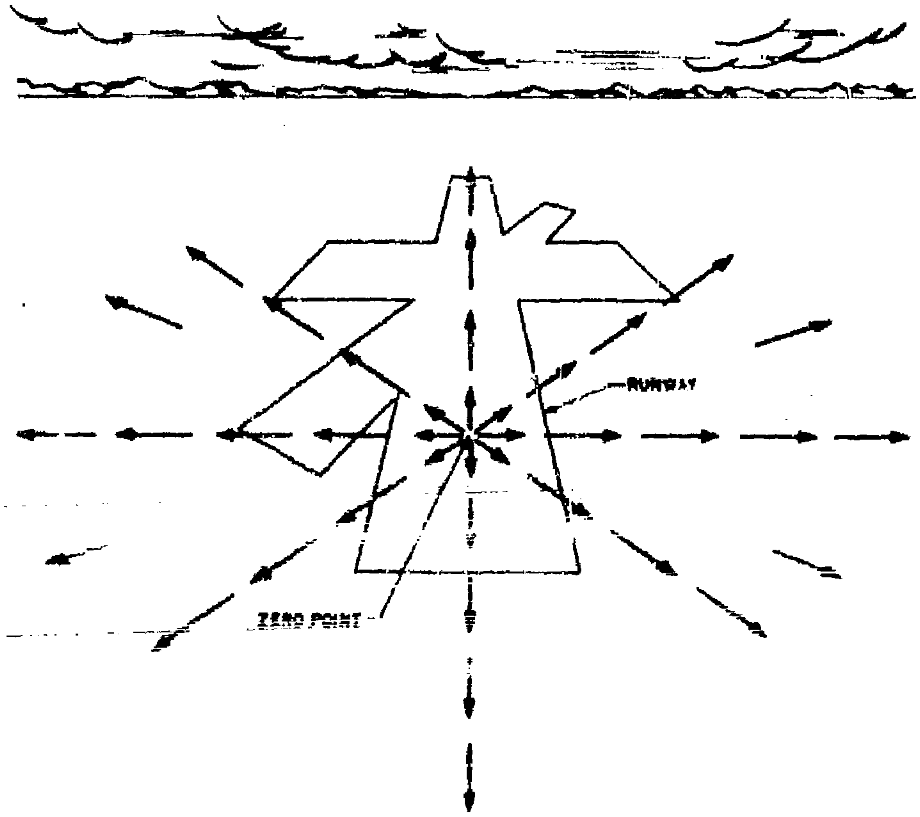


Figure 12.2. Expansion Pattern During Final Approach

The zero point is the direction of flight of the aircraft. The arrows show the direction in which details in the retinal images will move as the aircraft continues to approach. (after Andrews, T. G.,[12-11] Methods of Psychology)

Another study[12-24] makes somewhat the same conclusions. It points out that the apparent movement of objects in the pilot's visual field may furnish cues for his estimation of height during landings. It further suggests that the pilot might be able to land by these velocity cues alone.

How useful the foregoing type of analysis will be in solving problems of flying aircraft cannot be determined until more research is done.

Estimating Time of Touchdown. During the final phase of landing, just before touchdown, the pilot probably attempts, consciously or unconsciously, to estimate when his wheels will touch the runway; obviously, it is desirable that the wheels make contact at the proper point in the flare out. If the pilot thinks that he is higher than he actually is, he will "fly into the ground" before he can make a proper round out. If he judges he is lower than he actually is, he will round out too high, and then the aircraft will drop the remaining distance to the ground. Even in the so-called "wheel landings," where flying speed is maintained until the wheels are in contact with the runway, the pilot must judge how far the wheels are from the runway so that he can reach the desired airspeed at the time of touchdown. Yet the pilot never looks at his wheels, nor for that matter the runway under him, at any point in the landing. He seems to have built up from past experience an idea of how far below him his wheels actually are. Experience in taxiing may help him in this judgment. When he judges that his height above the runway is equal to his height when taxiing, he expects them to make contact. This type of judgment is much the same as the type an automobile driver makes when going through narrow spaces in traffic: he must judge whether his right fenders, which he cannot see, will clear the other cars. A person who can do this skillfully is said to "know his edges," or, to put it another way, employs the cue of motion parallax successfully.

Errors in Depth Judgment Vs. Size of Aircraft. In laboratory tests of relative depth judgment, the error (in units of distance, not necessarily in percent) increases with the amount of distance being judged. It is reasonable to expect that the same thing is true when a pilot attempts to judge his distance above the runway, though in this case the distance judgment is based more on memory of previous landings and taxiings than on actual perception of depth (because he cannot see directly below). If this is true, a pilot in a large transport or bomber, 20 feet or more above his wheels, will judge time of touchdown much more poorly than a fighter pilot seated close to his wheels. It seems probable that a landing under these conditions is more demanding on a pilot's skill and that there is some limit to the height at which cockpits can be set. The data with which to set this limit do not seem to be available now. Compensating for the greater cockpit height is the fact that the larger aircraft has greater flexion in the landing gear.

VISUAL AIDS FOR TAKE-OFF AND LANDING

Use of Visual Cues in Designing Landing Aids

Before runways can be marked to aid the pilot in landing, the designer must know what visual cues the pilot uses in landing; otherwise, the markings may be useless or even interfere with the pilot's ability to touch down at the correct point, speed, and angle of attack. The expansion pattern concepts described in the foregoing paragraphs are not fully developed, but they at least give designers a theory to go by in devising effective runway markers. Two investigators[12-25] have worked out the methods for developing markers on the expansion pattern theory; their methods may be applicable to other similar flight problems. Their basic assumption is that when the eye and brain can interpret an expansion pattern in more than one way, they will tend to choose the simplest. The runway represented in Figure 12.3, for example, can be interpreted as an irregular trapezoid being approached normally or as a rectangular runway seen from a banked aircraft. The latter is, of course, the simplest and correct solution.

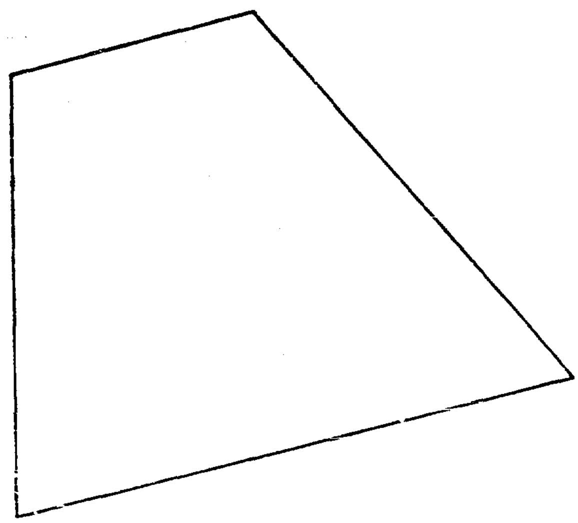


Figure 12.3. Is This Figure a Trapezoidal Runway Viewed Normally or a Rectangular Runway Viewed from a Banked Aircraft?

Runway Lights

At night or when visibility is poor during the day, the runway boundaries must be marked with lights so that the pilot can line up with the runway and land. These boundary-marking lights seem to represent the minimum cues that a pilot needs for landing; when no other lights are available for night landings, these lights are expected to supply cues available from other sources of stimulation during daytime operations. For example, the position of the long narrow rectangle of lights representing the runway provides a cue as to whether the approach angle of attack is correct. The perspective and amount of foreshortening in the rectangle tells the pilot whether he is at the correct height above the ground. If the apparent shape of the rectangle changes from a trapezoid to a lopsided quadrilateral, the pilot knows he is to the right or left of the proper approach path. From a study of runway perspective cues, plans have been devised[12-13] for a landing simulator based on deformations of the apparent shape of the runway.

A pilot approaching an unfamiliar airport may have trouble judging position by the shape of the rectangle outlined by runway lights. For example, after a few landings at one airport, he learns the length-to-width ratio for the runway that will show him he is approaching at the proper glide angle. If he goes into a strange airport where the runway is either shorter or wider and attempts to use the same perspective cues as before, he will be too high and come in at too steep an angle. Conversely, if the runway is longer or narrower, he will come in too low. These difficulties are to be expected from the geometry of the situation, and they are confirmed by pilots' experiences, though no experimental data are available. It can be argued that the runway light pattern should have constant dimensions for all airports. In fact, various articles[12-15] on this subject have suggested that a standard grid system of lights, which mark off known intervals along a runway, should be adopted.

It is not clear exactly how the pilot uses the configuration of the runway lights to establish the level of the horizontal ground plane on which to land the aircraft. Eye movement records have shown that fixation points were confined to a relatively small area straight ahead of the aircraft. On the basis of such a finding, one worker[12-30] recommended a lighting system that provides a single row of lights down the center of the runway. The difficulty here is that, even though the pilot is fixating more or less straight ahead, he may require visual cues from either side for landing efficiently. Such cues would be picked up in the periphery of his vision -- the "corner of his eye."

Another worker[12-18] has suggested that runway lighting problems could be studied better with airport lighting simulators than field tests. He also points out that all runway lighting systems, like runway markings, should tell the pilot how much of the runway has been used up and where he should turn off on taxiways.

Contrast Between Runway Lights and Background. A high brightness contrast between runway lights and background can give a pilot trouble in landing. The situation is similar to the one in which taxi lights are too bright (see Taxiing, below), but probably more serious, because landing is a more difficult and critical operation than taxiing. When bright runway lights are used on runways whose surfaces have low reflectance values, the runway appears as a dark area without substance, a "black hole." To partly solve this problem, runway lights have been devised that can be adjusted to any one of a logarithmic series of five brightnesses.[12-1,12-7] Thus, the brightness can be set at the level best suited to atmospheric conditions, time of day, etc. Candle powers required for lights to be seen at different distances through several kinds of atmospheric conditions are given in a study[12-27] conducted in 1947.

Directional runway lights, with fairly sharp cutoffs, have also been devised as a means of regulating brightness. Such lights radiate in all directions, but they are most intense in a relatively narrow beam. One standard light[12-8] in current use has two beams, 7 × 7 degrees in cross section, toed in toward the center of the runway. The amount of toe-in determines how far away a pilot on the center line of the runway must be to see each light at maximum intensity; for example, if they are toed in considerably, they will not appear bright until he is close to them. The lights are toed in less toward the far end of the runway. The beams are also angled upward at a small angle about equal to the glide slope of aircraft coming in for a landing. The net result is that when the pilot is on the proper glide slope and lined up with the runway, the lights appear almost equally bright over the entire length of the runway. Under the somewhat similar Bartow lighting system, both the intensity and the focus of the lights can be adjusted to perform optimally in any weather. The details of the system and the principles behind it are described in a brochure put out by a firm in Milwaukee, Wisconsin.[12-9]

Approach Light Systems

The visual cues provided by runway lights alone have been found to be inadequate for landings when visibility is very poor. As a consequence, much effort has been spent to perfect a system of approach lights extending out beyond the approach end of the runway. One study[12-18] describes three situations where approach lights are required to varying degrees: (1) landing on a clear night, when lighting of some sort is needed only for establishing the ground plane; (2) finding visual cues to make a visual landing after breaking out of an overcast; (3) using the approach lights only as a check in an instrument approach. The second situation is probably the most critical. (See Fig. 12.4.)

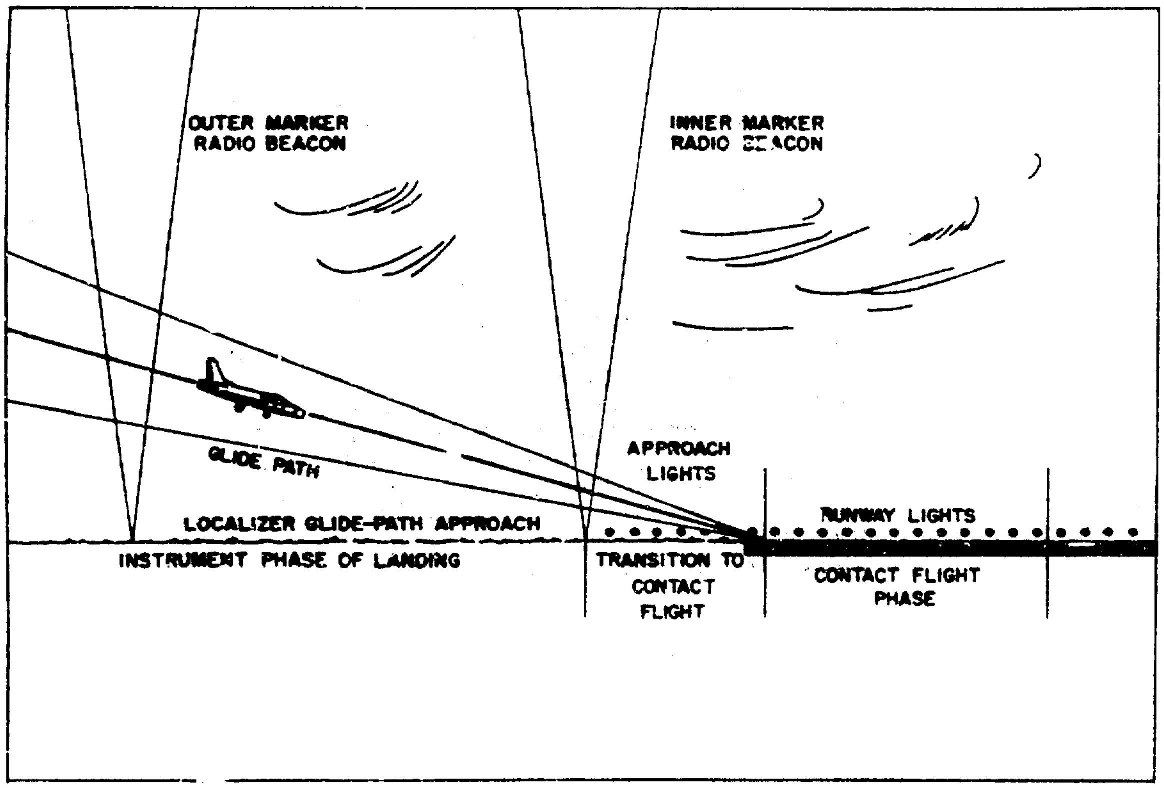


Figure 12.4. Transition From ILS to Visual Approach[12-9]

Any approach light system must be able to meet two types of visual requirements. First, it must supply all the cues needed to align the aircraft with the runway, to achieve and maintain a proper glide path, to aid in maintaining or adjusting the attitude of the aircraft, and to make the rapid, critical adjustments necessary for a safe touchdown. These requirements are usually met by the spatial patterning of the lights. Second, the pilot must see the approach light system far enough away, even through fog, haze, and precipitation, so that he can shift from instruments to visual flight before he has reached the point where he can no longer perform precisely enough on instruments.* This requirement is usually met by using intense lights and sometimes monochromatic lights.

*If instrument landing systems or GCA can bring a pilot safely all the way to the runway, this requirement will obviously be unnecessary.

In the United States, at least three approach light systems are recommended as standards and more than a dozen systems are in use; some of the latter are elaborate variations of one of the recommended standards.

Different types of light sources are also being tried out. They include flash tubes and neon bars, as well as more conventional lights. One hypothesis is that bars supply better cues than point sources for establishing orientation relative to the ground plane.

Approach Light Configurations. In a sense, a configuration of approach lights is a symbolic display. This means that the pilot must interpret the distortions in the configuration as he sees them from his aircraft before he can act on them. Obviously, the pilot must know the actual configuration before he can decide that he has a distorted view of it. The best configuration would of course be the one that gave the pilot the information he needed with the least amount of interpretation. Once such a configuration is agreed on, it can be made standard for all airports. The pilot will no longer be confused by not knowing which configuration he is looking at.

The current problem is to evaluate the various approach light systems now in use. There is little experimental evidence to determine which is best. Furthermore, as the investigator[12-18] has pointed out, pilots' opinions are not too helpful, because few have made enough approaches with each system to make an unprejudiced judgment. However, some of the studies available are reviewed in the following paragraphs.

One researcher[12-32] evaluated eight approach light systems by studying sets of perspective drawings. These drawings show how the light configuration would look to the pilot from twelve different situations on the approach. Included are views from an aircraft off course, in a bank, above and below the correct glide slope, and on the correct slope with wings level. Also shown is the condition where only the outer 1000 feet of the lights can be seen. Figure 12.5 shows the plan views (isometric for the slope line system) and wings-level perspectives for these eight systems. The researcher also provides windshield cutouts to show what portions of the approach light configuration would be cut off by the boundaries of the windshield. He concludes that all the systems considered give adequate directional guidance, provided the aircraft is in a wings-level attitude. Those systems with a horizontal reference provide better directional guidance than those without; in this respect, the slope line system was the best of all. In addition, the slope line system was the only one that permitted the pilot to estimate altitude. It was also reported to be the only one that furnished accurate information as to lateral position with respect to the approach axis regardless of aircraft attitude. But a system with a single center line and cross bars was recommended as supplying the best attitude reference.[12-15]

It must be pointed out that the foregoing conclusions seem to be based on inspection of the perspective drawings, not on any experimental data. Further, while the report tells in what qualities each system excels, it does not give any information on the relative importance of those qualities in operation.

Optical Illusions Due to Approach and Runway Lights. Several studies[12-3,12-6,12-15,12-30,12-32] have pointed up special difficulties or shortcomings common to many approach light systems.

First, there is the danger of confusing approach and runway lights. Approach lights must be mounted fairly close to the surface of the ground beyond the end of the runway. When a double row of approach lights joins with the boundary lights of the runway, pilots have reported confusion as to where the approach lights stop and the runway begins. The beginning of the runway must be clearly shown, either by having radically different runway and approach lights or by special boundary lights between the two.

Second, approach light systems should be designed so that they do not give false information or illusions. Three common illusions are as follows: (1) When flying into gradually thickening fog, the pilot feels he is climbing; to compensate, he descends too low. (2) Under some conditions, the aircraft seems to be higher when it is in a bank than when its wings are level. (3) The pilot gets the impression he is in a bank when one row of runway lights is brighter than the other. One study[12-30] pointed out a fourth illusion: When a single row of lights runs down the left-hand side of the approach path, the pilot misinterprets the perspective and "corrects" to the right; he ends up too far to the right as he crosses the runway threshold.

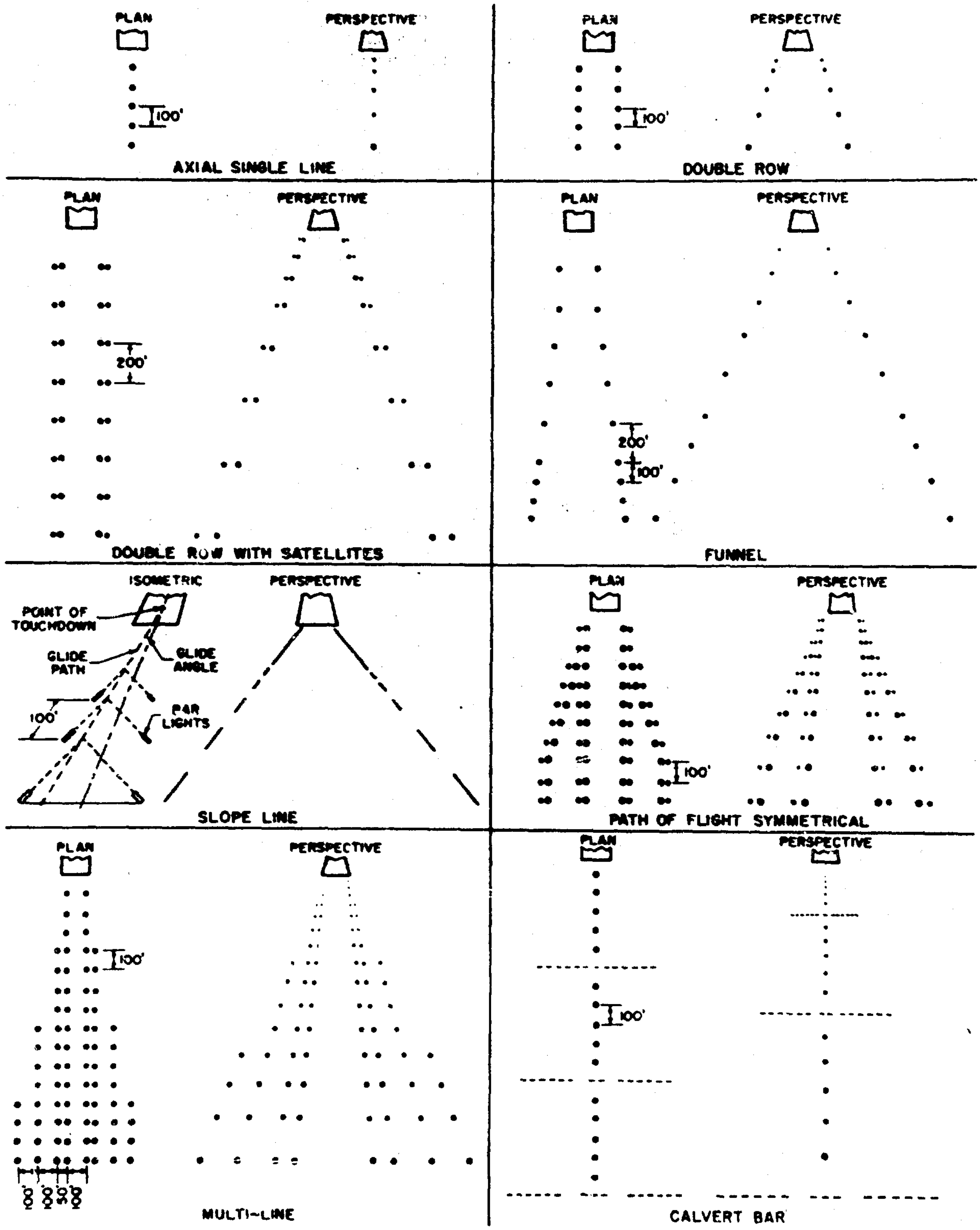


Figure 12.5. Eight Approach Light Systems

The perspectives show the systems as they would appear on a proper glide slope and path. (after Warren[12-32])

Intensity of Approach Lights. The optimum intensity for an approach light system is influenced by several factors. First of all, the lights should be designed so that their intensity may be varied to suit the weather conditions that exist when the system is being used. When visibility is restricted, the lights should be made bright to get as much penetration as possible. However, under some conditions, there is an upper brightness limit; in fog, for example, too-bright approach lights turn the whole approach light system into a diffuse "glob" of light. Under any conditions, the lights will glare or dazzle the pilot if their intensity is above a certain level determined by time of day, atmospheric conditions, and distance and direction from the aircraft. As a pilot approaches a light system, there will be some point at which the lights come into view. As he approaches closer, the lights will tend to glare. The ideal is to have as great a range between the point of visibility and the point of glare as possible. Investigators have worked out the relationship between visibility and glare for different conditions of atmospheric interference and for day and night conditions. Their report[12-22] recommends intensity settings for the standard 250-watt bulb for different horizontal visibilities. It also recommends improvements in the design of slope-line approach light systems.

Attempts are being made[12-7] to construct a device that will (1) automatically measure visibility at the end of the runway and (2) adjust the intensity of the approach lights in such a manner as to reduce glare while maintaining as much penetration as possible.

Runway Markings

When daytime visibility is low but over-all illumination is relatively high, a runway marking system can be expected to aid the pilot in landing his aircraft. Such a marking system should be designed to show the direction of the runway clearly, so that the pilot can align his aircraft with it. Marking systems may also be designed to show the pilot where he is on the runway after landing, i.e., how much of the runway has been used up. Three studies show the type of work that has been done in this area.

Chevron Systems. One team of investigators[12-26] first attempted to find the best shape for a runway marking. They sought one that would (1) have directional qualities and (2) be visible the greatest distance under adverse visibility conditions. They used markings painted on a moving belt, which they viewed through ground glass to simulate fog. Of the nine markings tried out, a chevron-type mark turned out to have the greatest "recognition distance."

In a follow-up study[12-20] chevrons were tried out on runways oriented so that those on either end pointed toward the middle. In addition, chevrons were grouped in varying numbers to give an indication of how far each group was from the end of the runway. For example, on a 7000-foot runway, three chevrons were grouped near each end of the runway pointing toward the middle. A thousand feet from each group of three chevrons was a group of two; 1000 feet each side of the middle were single chevrons; and for runways that had the same number of chevrons at each end, a bar was located at the middle. Figure 12.6 shows half of such a runway.

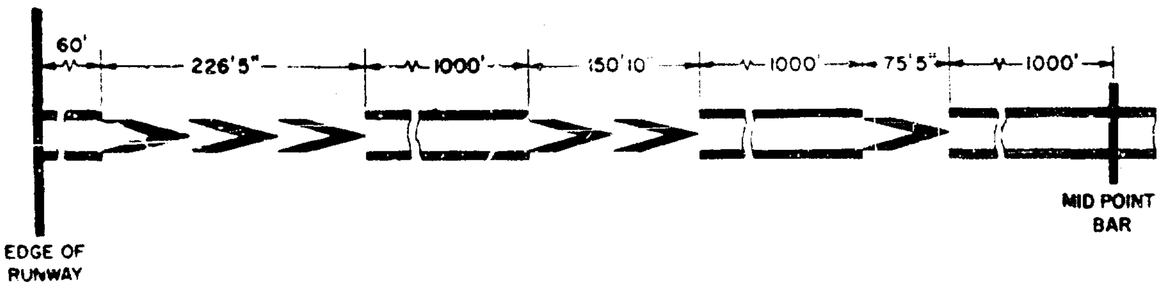


Figure 12.6. Chevrons Marking Runway Intervals and Aiding Pilot to Line Up With Runway (Gerathewohl[12-19])

Laboratory studies and flight checks indicated that the best chevrons were 12 feet wide, had 100-foot arms forming a 30-degree angle, and were made of black material with a yellow border. It was feared that the chevrons would create "roof peak" illusions, but flight checks showed that they did not. The authors suggested that the same system might be adapted to night landings by using

transilluminated panels set into the runway. Such a system could be expected to provide a larger illuminated surface on which to land than conventional runway boundary lights. Being large, its brightness could be kept low, thus providing a "flat" rather than "contrasting" type of illumination.

Mirror Landing Systems. A mirror landing system has been developed as a visual aid to pilots attempting to establish the proper glide angle on an approach.[12-4] The system operates so that the pilot sees a light reflected from a mirror at one side of the runway. When the light is in the center of the mirror, the pilot is approaching at the proper angle; vertical and horizontal rows of lights parallel to the center lines of the mirror show him whether he is holding the reflected light from the mirror in the proper position. The device was first developed by the British to perform the same function as an LSO (the officer who flags aircraft in) during a carrier landing. The device, which might be useful in non-carrier landings also, is now being studied and developed further by several agencies.

Mirrors have also been studied to aid the pilot in establishing and maintaining the proper climbing attitude following take-off. (This is of particular importance for catapult take-offs.) The Naval Air Test Center examined the use of windshield markings in conjunction with a mirror.[12-5] The mirror was used to aid the pilot in finding and maintaining the proper eye level position. The position of the mark on the windshield relative to the eye level was computed on the basis of aerodynamic considerations. However, tryouts with this system disclosed that neither forward nor side markings on the canopy were of assistance, because the pilots could not maintain the proper eye level position. In addition, it was pointed out that the device could not be used where the horizon was not visible or was indistinct.

Taxiing

A pilot has two chief problems while taxiing an aircraft. The first is to be sure that all parts of the aircraft clear ground obstacles and other aircraft. The second is to be able to find his way around the airport to his parking place or to the take-off positions at the end of the runways. Both of these problems can be relieved by removing restrictions to visibility or keeping them at a minimum.

During the day, the chief problem is obstructions to the pilot's vision. Either he must have an unobstructed view from the cockpit, or obstructions must be taken into account in taxiing procedures and airport design. In most tailwheeled aircraft, forward visibility is poor during taxiing; generally the pilot must look at objects close at hand through his side panels. Since it is often impractical to redesign aircraft to improve this feature, efforts should be made to keep the taxiways clear of obstructions and to put signs and other markings where the pilot can see them easily through his side panels.

Accidents involving misjudgement of wing tip clearance are less serious than head-on collisions, but they occur more frequently. In judging the clearance between wing tips and obstacles, the error tends to be proportional to wing length (just as errors in judging height above the runway tend to increase with the height of the pilot above the wheels). This means that for aircraft with very long wings, the pilot must allow for a larger margin of safety. As a consequence, ramp space must be provided to insure wing tip clearance that could otherwise be used for other purposes. However, when markers on which to align the wheels are painted on the ramp, space can be saved; since the wheels are closer to the pilot than the wing tips, the error of judgment is smaller, and less space need be set aside to allow for a margin of safety.

Illuminating Taxiway. Taxiing at night or during poor daytime visibility presents a variety of visual problems, most of them having to do with illumination. Three kinds of lighting are employed to make taxiing at night safer. The first is the use of taxiway and obstruction lights. Different colors are usually used for marking taxiways or obstructions. These lights should be placed so that they can be seen through the windshield. In addition, they should be spaced close enough together so that there is no ambiguity as to the shape of the area or object that they outline.

A second type of illumination is floodlighting. Floodlights usually provide good visibility in the area illuminated but tend to destroy dark adaptation. They also make it very difficult to see objects outside the illuminated area.

The third method of illumination is by means of aircraft taxi lights, which are attached to the aircraft and shine ahead. Close objects are most brightly illuminated; glare is often produced, particularly when bright landing lights are also used as taxi lights. Unless taxi lights are adjustable or are attached to the steerable nose wheel, they illuminate the area straight ahead of the aircraft. During turns, the area toward which the aircraft is turning will thus be in darkness. When aircraft have taxi lights, reflectors can be used to mark taxiways.

An evaluation of one experimenter's taxi light[12-2] resulted in the following recommendations:

1. Taxi lights mounted on the nose wheel are useful for taxiing in unlighted areas.

2. Using taxi lights intermittently, to keep them from overheating, is not safe.

3. Taxi lights that sweep across the taxi area at adjustable frequencies were found to be unsatisfactory at any speed.

4. There is probably an optimum ratio of brightness to beam width for taxi lights, but it has not yet been determined.

With all three methods of illumination, the chief problem is to prevent too high a brightness contrast. For example, the space between bright taxi-way lights is a black area devoid of detail or texture; the pilot can only guess what is in such areas. When the brightness of these lights is reduced, the texture of the area between the lights can be made out, and the pilot becomes confident that he can taxi safely over this surface. Similarly, flood lights produce black shadows. The goal of night illumination should be to light the taxiing area as uniformly as sunlight, even though the illumination is at a lower level. One difficulty is that the lights themselves must be very bright if the objects in their beams are to be visible at all; and,when these lights get into the visual field, they tend to raise the threshold to such a level that the pilot cannot see into the darker areas. Another difficulty is that marker lights must be bright enough to be seen under bad atmospheric conditions and at some distance. When bright enough for these purposes, they will be too bright when the aircraft is taxiing close to the lights. However, these difficulties are not critical. The future development of lighting should probably be directed toward supplying more uniform illumination, such as can be achieved with transillumination.

<u>Visual Aids for Maintaining Orientation While Taxiing.</u> Visual aids such as signs, markers, and maps of the runways and taxiways are most helpful in establishing and maintaining orientation in the airport. Obviously, letters and numerals should be of size, type face, color, brightness, etc., for best readability. In addition, signs should be located so that they may be seen easily from the cockpit. For example, a sign with small letters is difficult to read when positioned so that the plane of the sign is perpendicular to the axis of the taxiway. At a distance, it is too far away to read or is blocked out by the nose. As the aircraft gets closer, the angle at which it is viewed through the cockpit side panels becomes more oblique; it is still difficult to read. By placing the sign so that it is viewed perpendicular from the position at which it is intended to be read and using type of the design and size most appropriate for this distance, these difficulties can be overcome.

Runway directions and directions from one area to another in an airport are defined in compass directions. It is therefore helpful to have signs or markings showing the direction of north and other cardinal compass points.

LIST OF REFERENCES

12-1 Anon. Brightness Setting of Runway and Approach Lights, Airfield Lighting Equipment. Tech. Order No. 08-20-76. Dept. of Air Force, Hq. USAF, Washington, D. C. 1954.

12-2 Anon. Comparison of Taxi Light Systems. Naval Air Test Center. 1954.

12-3 Anon. Evaluation of Airport Lighting. Flight Tech. Group, International Air Transport Association.

12-4 Anon. Fury's Pioneer Mirror Landings. Royal Navy, Great Britain.

12-5 Anon. Indicator for Airplane Attitude in Take Off. Naval Air Test Center.

12-6 Anon. Installation and Evaluation of the Navy Composite Approach Lighting System. Naval Air Test Center. 1953.

12-7 Anon. Installation and Test of Automatic Light Intensity Control System for Approach and Runway Lights. Naval Air Test Center. 1952.

12-8 Anon. Light, Runway Marker, Elevated, Type C-1. Military Specification MIL-L-5904B. May 24, 1951.

12-9 Anon. The Lights That Bring Them In. Line Material Company, Milwaukee, Wis. 1946.

12-10 Anon. The Relation of Human Factors to Jet Fighter Accidents. Office of the Inspector General, Norton AFB, California. July 26, 1954. p. 81.

12-11 Andrews, T. G., Methods of Psychology. John Wiley and Sons, New York, N. Y. 1948.

12-12 Barr, N. L., Hussman, T. A., and Parker, J. F., The Visibility of Airport Runways. Naval Med. Research Inst. Nat. Naval Med. Center, Bethesda, Md. Project TED PTR AC233, Research Report 001 086.07.03. 1954.

12-13 Bell, J. M., A Landing Display for Use with a Contact Flight Simulator. University of Ill., SDC Human Engineering Project 20-L-1, Report No. 71-16-6. March 1951.

12-14 Berry, Richard N., Riggs, L. A., and Duncan, C. P., "The Relation of Vernier and Depth Discrimination to Field Brightness," J. Exp. Psychol. Vol. 40. No. 3. June 1950.

12-15 Calvert, E. S., The Integration of Visual Landing Aids, with Particular Reference to Proposal Submitted by Capt. G. J. Malouin to the Meeting of the Flight Technical Group of I.A.T.A. Royal Aircraft Establishment, Farnborough, England. 1951.

12-16 Edwards, T. M., and Howell, W. D., A Study of Pilots' Eye Movement During Visual Flight Conditions. CAA Tech. Devel. Report No. 179. Civil Aeronautics Administration, Ind. January 1952.

12-17 Ellis, W. H. B., and Allan, R. N., Pilots' Eye Movements During Visual Approaches and Landings. FPRC 888, Great Britain. September 1954.

12-18 Fitts, P. M. (Editor), Human Engineering For an Effective Air Navigation and Traffic Control System. NRC Committee on Aviation Psychology. Washington, D. C. 1951.

12-19 Gerathewohl, S. B., and Haber, H., A Study of Runway Markings and a Proposed Runway Identification Lighting System. Project No. 21-02-057, USAF School of Aviation Medicine, Randolph Field, Texas. 1949.

12-20 Gerathewohl, S. S., Haber, H., Byrnes, B., Rippk, P. H., and Patterson, W. M. A Study of Runway Markings. Project No. 21-24-001, Report No. 4. USAF School of Aviation Medicine. Randolph Field, Texas. 1950.

12-21 Gibson, J. J., "The Visual Perception of Objective Motion and Subjective Movement." Psychol. Rev. Vol 61. No. 5. 1954. pp. 304-314.

12-22 Gilbert, M. S. and Pearson, H. J. C., A Study of the Visibility and Glare Range of Slope-Line Approach Lights. CAA Tech. Devel. and Eval. Center, Tech. Report No. 150, Indianapolis, Ind. 1951.

12-23 Gornee, H., "The Effect of Visual Stimulus Upon the Perception of Bodily Motion." Amer. J. Psychol. Vol. 43. 1931. pp. 26-48.

12-24 Grindley, G. C., Notes on the Perception of Movement in Relation to the Problem of Landing an Airplane. Great Britain Flying Personnel Research Committee, Report No. 426. March 1941. p. 10.

12-25 Hochberg, J., and Smith, O., "Landing Strip Markings and the Expansion Pattern. I. Program Preliminary Analysis and Apparatus." J. Perceptual and Motor Skills. Cornell University, File II B 5. January 3, 1955.

12-26 Jennings, A. A., Haber, H., and Gerathewohl, S. S., A Study of Runway Markings. Report 1, Project 512, School of Aviation Medicine. November 1947. p. 14.

12-27 Kevern, G. M., Effect of Source Size Upon Approach Light Performance. U. S. Army Air Forces, Material Command, Engineering Division, Equipment Laboratory. April 21, 1947. p. 9.

12-28 Pfaffman, C., "Aircraft Landings without Binocular Cues; A Study Based Upon Observations Made in Flight." Amer. J. Psychol. Vol. 61. July 1948. pp. 323-334.

12-29 Pfaffman, C., An Experimental Study of Depth Perception in Landing Airplanes.

12-30 Robson, R. C., "Trapped in the Approach Light Bog." Aviation Week. Vol. 64. No. 17 and No. 18. 1956.

12-31 Tiffin, J., and Bromer, J., Analysis of Eye Fixations and Patterns of Eye Movements in Landing a Piper Cub J-3 Airplane. Report No. 10. CAA Division of Research, Washington, D. C. 1943.

12-32 Warren, R. E., Perspective Analysis of Approach Light Patterns. CAA Tech. Devel. Report 96. Civil Aeronautics Administration. August 1949.

12-33 Witkins, H. A., "Further Studies of the Perception of the Upright When the Direction of the Force Acting on the Body is Changed." J. Exp. Psychol. Vol. 43. 1952. pp. 9-20.

12-34 Witkins, H. A., "Perception of the Upright When the Direction of the Force Acting on the Body is Changed." J. Exp. Psychol. Vol. 40. 1950. pp. 93-106.

12-35 Zeller, A. F., Harvey, E. S., and Burke, J., A Study of Undershoot-Overshoot Non-Emergency Accidents. Directorate of Flight Safety Research, Office of Inspector General, USAF Norton AFB, Calif. 1955.

12-36 Anon. Final Approach Visibility Studies. U. S. Dept. of Commerce, Weather Bureau. April 1955.

12-37 Anon. Flight Test of Approach Light System. Naval Air Test Center. 1952.

12-38 Anon. Problems Affecting Approaches and Landings. Empire Central Flying School. March 1942.

12-39 Atkinson, R. C., and Ammons, R. B., "Experimental Factors in Visual Form Perception: II. Latency as a Function of Repetition." J. Exp. Psychol. Vol. 43. No. 3. March 1952. pp. 173-178.

12-40 Bartlett, N. R., and MacLeod, S., "Effect of Flash and Field Luminance Upon Human Reaction Time." J. Opt. Soc. Amer. Vol. 44. April 1954. pp. 306-311.

12-41 Biel, W. C., and Brown, G. E., Jr., Estimation of Airplane Speed and Angle of Approach. U. S. Navy, Office of Naval Research Contract N6-ori-139, Denison University, Final Report. March 1949.

12-42 Breckenridge, F. C., and Douglas, C. A., "Development of Approach-and-Contact-Light Systems." Illum. Engng. Vol. 40. 1945. pp. 785-829.

12-43 Brown, F. R., and Laso, J., Study of Requirements for Carrier Aircraft Approach Light System. Part II. A Comparative Evaluation of the Tri-Color Sector, The Airspeed Controlled, Attitude Gyro-Controlled and the Angle of Attack Controlled Approach Light Systems. Report TED NAM EL-614 Part 2. Naval Air Material Center. Philadelphia, Pa December 1951.

12-44 Calvert, E. S., An Outline of the Theoretical and Experimental Basis for the Standardization of the Visual Aids on Civil Airports. Tech. Memo. No. EL. 1509, September 1949, for meeting I.E.S. Committee on Aviation Lighting, Indianapolis, Ind. October 24-25, 1949.

12-45 Collier, R. M., "An Experimental Study of Form Perception in Indirect Vision." J. Comp. Psychol. Vol. 11. February 1931. pp. 281-290.

12-46 Crannell, C. W., and Cristensen, J. M., Expansion of the Visual Form Field by Perimeter Training. WADC Tech. Report 55-368. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. 1955.

12-47 Davenport, W. W., and Woodson, W. E., The Design of a Navy Air Traffic Control Tower. U. S. Navy Electronics Laboratory, San Diego, Calif. Report 490. 1954.

12-48 DeBoer, J. B., Calculations on the Light Distribution of Approach and Runway Lights. Philips Research Report 6: 241-50. August 1951. (N. V. Philips' Gloeilampenfabrieken, Eindhoven, Netherlands).

12-49 DeBoer, J. D., Visibility of Approach and Runway Lights. Philips Research Report 6: 224-39. June 1951. (N. V. Philips' Gloeilampenfabrieken, Eindhoven, Netherlands).

12-50 Douglas, C. A., Some Factors Affecting the Relation Between Reported Visibility and Visibility from Aircraft. U. S. Dept. of Commerce, Nat'l. Bur. of Standards. Report 2715, Project 0201-20-2301. BuAer, Visual Landing Aids Section Project No TED NBS AE-10006. August 12, 1953.

12-51 Douglas, C. A., and Young, L. L., Development of a Transmissometer for Determining Visual Range. CAA Tech. Devel. Report 47. Civil Aeronautics Administration, Washington, D. C. 1945.

12-52 Dunbar, C., Fundamental Principles of Meters Used to Measure Visibility. Paper read before the Photometry Section on April 4, 1939.

12-53 Duntley, S. Q., and Blackwell, H.R., A Program of Military Visibility Research. Armed Forces-National Research Council Vision Committee. Reprinted from Minutes of 32nd Meeting. April 2-4, 1953.

12-54 Eckstrand, G. A., Cue Attention Habits as a Factor in Training. WADC Tech. Report No. 6566. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. August 1951.

12-55 Edgerton, H. A., and Fryer, D. H., The Development of an Evaluation Procedure for Training Aids and Devices. Special Devices Center, TR SDC 383-2-1. Richardson, Bellows, Henry & Co., Inc., Project 181. June 1950.

12-56 Flexman, Ralph E., Matheny, William G., and Brown, Edward L., "Evaluation of the School Link and Special Methods of Instruction in a Ten-Hour Private Pilot Flight-Training Program." University of Illinois Bulletin. Vol. 47. No. 80. July 1950.

12-57 Fry, G. A., and Cobb, P. W., "Visual Discrimination of Two Parallel Bright Bars in a Dark Field." Amer. J. Psychol. [illegible]

12-58 Gerathewohl, S. J., and Cibis, P. A., "The Space Between Distinct Contours." Amer. J. Psychol. Vol. 66. 1953. pp. 436-446.

12-59 Gerathewohl, S. J., and Haber, H., A Proposed Runway Identification Lighting System. Project 21-02-007, Report 3. USAF School of Aviation Medicine, Randolph Field, Texas. April 1949.

12-60 Gibson, J. J., A Theory of Pictorial Perception. U. S. Air Force, Air Research and Devel. Command, Human Factors Operations Research Lab. (Revision of Memorandum Report No. 35. May 1953) Contract No. AF 33(038)22804. 1954.

12-61 Gibson, J. J., Proposals for a Theory of Pictorial Perception. U. S. Air Force, Air Research and Devel. Command, Human Factors Operations Research Lab. Memo Report No. 35, Contract AF 33(038)22804, Cornell University. Ithaca, N. Y. Ad-22 065. May 1953.

12-62 Gibson, J. J., "The Perception of Visual Surfaces." Amer. J. Psychol. Vol. 63. July 1950. pp. 367-384.

12-63 Gibson, J. J. (including comments by Gagne, R. M., and Verplanck, W. S.). The Possibilities of Research on Training in Recognition and other Visual Performances. Report to Armed Forces - National Research Council Vision Committee. August 25, 1948.

12-64 Gilbert, M. S., Development of Airport Control Tower Lighting. Tech. Devel. Report No. 82, Civil Aeronautics Administration, Indianapolis, Ind. April 1949.

12-65 Gilbert, M. S., A Low Cost Boundary Lighting System for Small Airports. Tech. Devel. Report No. 53, Civil Aeronautics Administration, Indianapolis, Ind. August 1947.

12-66 Gilbert, M. S., and Faucett, R. E., The Development of Airport Taxi Guidance Signs. Tech. Devel. Report No. 170, Civil Aeronautics Administration, Indianapolis, Ind. June 1952.

12-67 Gilbert, M. S., and Hemelt, B. A., The Development of an Airport Taxi Guidance System. CAA Tech. Devel. Report No. 171, Civil Aeronautics Administration, Indianapolis, Ind. June 1952.

12-68 Gilbert, M. S., and Pearson, H. J. Cory, *An Analysis of the Candlepower Distribution Requirements of Runway Lights.* Tech. Devel. Report No. 178. Civil Aeronautics Administration, Indianapolis, Ind. June 1952.

12-69 Gilbert, M. S., and Pearson, H. J. C., *Development of a Retractable Slope-Line Approach-Light Unit.* CAA Tech. Devel. Report No. 156. Civil Aeronautics Administration, Indianapolis, Ind. January 1952.

12-70 Gilbert, M. S., Pearson, H. J. C., and Adkins, H., *Evaluation of a Controllable-Beam Runway Light.* CAA Tech. Devel. and Eval. Center Report No. 238. June 1954.

12-71 Gilinsky, A. S., *Perception of Size of Objects at Various Distances.* Contract AF 18(600)-196, Project 7703, Task 77110, Research Bull. AFPTRC, Air Research and Devel. Command, Armament Systems Personnel Research Lab., Lowry Air Force Base, Col. (Columbia University) December 1954.

12-72 Graham, C. H., *Some Factors that Limit Vision.* U. S. Navy Office of Naval Research, Monthly Research Report. September 1951. pp. 16-25.

12-73 Graham, C. H., Hammer, E. R., Mueller, R. D., and Mote, F. A., "Stereoscopic Settings with Stimulus Providing Multiple Reference Ranges. The Perception of Spatially Repeating Patterns." *J. Psychol.* Vol. 27. 1949. pp. 209-216.

12-74 Graham, C. H., and Venlar, F. A., "The Influence of Size of Test-Field Surround on Visual Intensity Discrimination." *Proc. Nat. Acad. Sci.* Vol. 36. Washington, D. C. January 1950. pp. 17-25.

12-75 Graybiel, A., Hupp, D. I., Patterson, J. L., Jr., "The Law of the Otolith Organs." *Federation Proc.* Vol. 5. No. 36. 1946.

12-76 Gruber, H. E., and Clark, W. C., "Perception of Slanted Surfaces." *Perceptual and Motor Skills.* Vol. 6. 1956. pp. 97-106.

12-77 Harrison, J. M. and Phoenix, C., *The Effects of Visual Angle and Degree of Imperfection upon the Recognition of Objects.* Contract AF 33(616)432, Tech. Note No. 104. Boston University Optical Research Lab., Boston, Mass. September 1953.

12-78 Hastorf, A. H., and Way, K. S., "Apparent Size with and without Distance Cues." *J. Gen. Psychol.* Vol. 47. 1952. pp. 181-188.

12-79 Hermans, T. G., Loucks, R. B., Checov, L., and Stern, F., *Annotated Bibliography on the Psychological Aspects of Orientation as They Relate to Aviation.* Aero Medical Lab., Eng. Div., Air Materiel Command, Wright Field, Dayton, Ohio. (University of Washington Aviat. Psychol. Project) December 1947.

12-80 Hockberg, J. E., Gleitman, H., and MacBride, P. D., "Visual Thresholds as a Function of Simplicity of Form." *Amer. J. Psychol.* Vol. 3. 1948. pp. 341-342.

12-81 Holway, A. H., and Boring, E. G., "Determinants of Apparent Visual Size with Distance Variant." *Amer. J. Psychol.* Vol. 54. 1941. pp. 21-37.

12-82 Hulburt, E. O., "Optics of Searchlight Illumination." *J. Opt. Soc. Amer.* Vol. 36. August 1946. pp. 483-491.

12-83 Kevern, G. M., Approach and Runway Lighting for Adverse Weather Conditions. *Illum. Engng.* Vol. 41. June 1946. pp. 455-473.

12-84 Kevern, G. M., Standard Procedure for Calculating Effectiveness of Approach and Runway Lights During Low Visibility Conditions. June 11, 1948.

12-85 Knoll, H. A., Beard, D. B., Tousey, R., and Hulbert, E. O., Threshold and Signalling Ranges of Point Sources of Light in Fields of Brightness from Dark to Daylight. U. S. Naval Research Lab. Report No. H-2627. October 11, 1948.

12-86 Kristofferson, A. B., Preliminary Study of the Sensitivity Gradient of the Central Fovea. University of Michigan Vision Research Lab., Optics and Vision Group Project 2144-312-M, Research Report 11. June 30, 1955.

12-87 Kristofferson, A. B., Foveal Intensity Discrimination as a Function of Area and Shape. 1954.

12-88 Kurke, M. I., "The Relation of Practice to Development of Visual Perception." Psychol. Newsletter. Vol. 40. 1953. pp. 1-9.

12-89 Lane, J. C. and Cummings, R. W., The Role of Visual Cues in Final Approach to Landing. Aero. Research Lab., Dept. of Supply, Melbourne, Australia. 1954.

12-90 Lean, D., Interim Note on Trials with an Optical Glide Path Indicator. Tech. Memo. No. Aero. 520. December 1952.

12-91 Leibowitz, H. W., Myers, N. A., and Grant, D. A., "Frequency of Seeing and Radial Localization of Single and Multiple Visual Stimuli." J. Exp. Psychol. Vol. 50. 1955 pp. 369-373.

12-92 Leibowitz, H. W., Myers, N. A., and Grant, D. A., "Radial Localization of a Single Stimulus as a Function of Luminance and Duration of Exposure." J. Opt. Soc. Amer. Vol. 45. 1955. pp. 76-78.

12-93 Mann, C. W., "Visual Factors in the Perception of Verticality." J. Exp. Psychol. Vol. 44. 1952. pp. 460-464.

12-94 Mann, C. W., Studies in Space Perception. U. S. Naval Air Station, Pensacola, Fla., School of Aviation Medicine and Research Project NM 001 063.01.18, Joint Project Report No. 18. October 31, 1950.

12-95 Mann, C. W., and Berry, N. H. The Perception of the Postural Vertical. Report No. 2 Visual Factors. Joint Project Report No. 5, Tulane University Project N7onr-434 T.O. I, Office of Naval Research, Project Designation NR 140:455, School of Aviation Medicine, Project NM 001 037. June 23, 1949.

12-96 Mann, C. W., Berthelot-Berry, N. H., and Dauterive, H. J., Jr., "The Perception of the Vertical: I. Visual and Non-Labyrinthine Cues." J. Exp. Psychol. Vol. 39. 1949. pp. 538-547.

12-97 Mann, C. W., and Dauterive, H. J., Jr., The Perception of the Postural Vertical Rep. No. 1. The Modification of Non-Labyrinthine Cues. Joint Project Report No. 4. Tulane University, Contract N7onr-434, Task Order I, Office of Naval Research, Project Designation NR 140-455, U. S. School of Aviation Medicine and Research Project No. NM 001 037. June 3, 1949.

12-98 Mann, C. W., and Passey, G. E., The Perception of the Vertical: 8. Adjustment to the Vertical as a Function of the Magnitude of Tilt and the Duration of Exposure. U. S. Naval Air Station, Pensacola, Fla., School of Aviation Medicine and Research Project NM 001 063.01.14, Joint Project Report No. 14. February 24, 1950.

12-99 Mann, C. W., and Passey, G. E., The Perception of the Vertical. V. Adaptation Effects. Joint Project Report No. 9, Tulane University Contract N7onr-434, Task Order I, Office of Naval Research, Project Designation NR 140-458, U. S. Naval School of Aviation Medicine and Research and BuMed and Surg. Project No. NM 001 037. November 17, 1949.

12-100 Mann, C. W., Passey, G. E., and Ambler, R. K., The Perception of the Vertical,7. Effect of Varying Intervals of Delay in a Tilted Position upon the Perception of the Postural Vertical. U. S. Naval Air Station, Pensacola, Fla., School of Aviation Medicine and Resea Project NM 001 063.01.12. Joint Project Report No. 12. January 25, 1950.

12-101 Matheny, B. J., Two Simulators for Training Pilots and Controllers in Air Traffic Control Procedures. U S Navy, Office of Naval Research, Special Devices Center Report 71-16-15. June 20, 1955.

12-102 Pearson, H. J. C., Modification of the Slope Line Approach Light System. CAA Tech. Devel. Report No. 167. Civil Aeronautics Administration. April 1952.

12-103 Pearson, H. J. C., The Slope Line Approach Light System. CAA Tech. Devel. Report No. 104. Civil Aeronautics Administration. March 1950.

12-104 Pearson, H. J. C., and Gilbert, M. S., An Experimental Counterrotating Marker Beacon. CAA Tech. Devel. Report No. 160. Civil Aeronautics Administration. February 1952.

12-105 Pearson, H. J. C., and Gilbert, M. S., Some Considerations of High Intensity Approach Lighting. CAA Tech. Devel. Report No. 60. Civil Aeronautics Administration. March 1947.

12-106 Rock, Irvin, "The Perception of the Egocentric Orientation of a Line." J. Exp. Psychol. Vol. 48. 1954. pp. 367-374.

12-107 Shetler, W. L., Barbert, J. H., and Finney, W. J., Some Aspects Affecting the Recognition of a Linear Pattern Viewed Against a Random Field.

12-108 Sleigh, R. B., and Duvoisin, G., An Annotated Bibliography of Form Perception. Special Devices Center Report 166-I-152. Johns Hopkins University. 1952. distributed by the U. S. Dept. of Commerce, Office of Technical Services, Washington 25, D.C. PB 111516.

12-109 Spencer, J., Judgment of Height by the Apparent Obliquity of Familiar Ground Outlines. Flying Personnel Research Committee Report No. 819. Great Britain. March 1953.

12-110 Tiedemann, Arthur T., A Lighting Pattern for Runway Zone Identification. CAA Tech. Devel. Report No. 208. Civil Aeronautics Administration. December 1954.

12-111 Tiedemann, A. T., Lighting Pattern Distortion Caused by Rain on an Airplane Windshield. CAA Tech. Devel. Report No. 189. Civil Aeronautics Administration. January 1953.

12-112 Wapner, S., and Witkin, H. A., "The Role of Visual Factors in the Maintenance of Body-Balance." Amer. J. Psychol. Vol. 63. 1950. pp. 385-408.

12-113 Warren, Roy E., Perspective Analysis of the Proposed ALPA Approach Light System. A Supplement to Technical Development Report No. 96, Perspective Analysis of Approach Light Patterns. CAA Tech. Devel. Report No. 133. Civil Aeronautics Administration. January 1951.

GENERAL BIBLIOGRAPHY (Cont)

12-114 Warren, Roy E., and Pearson, H. J. Cory, 30-Degree Modified Slope-Line Approach-Light System. CAA Tech. Devel. Report No. 137. Civil Aeronautics Administration. February 1951.

12-115 Weiner, M., "Effects of Training in Space Orientation on Perception of the Upright." J. Exp. Psychol. Vol. 49. May 1955. pp. 367-373.

CHAPTER 13

FACTORS INFLUENCING VISION WITHIN THE AIRCRAFT

The discussion of visual flight presents problems that are quite different from those for instrument flight. The reasons for this are significant. The history of visual flight is much longer than that of instrument flight. Consequently, we have available more accounts of problems arising during various phases of visual flight. Instrument development has, of necessity, been so rapid that there has rarely been time for evaluating a particular device before it was obsolete. As a result, this chapter on instrument flight will seem to contain more detailed information on various aspects of the internal environment of the aircraft than that describing the design rules for future developments.

At the time of writing, it is conceivable that we are in a period of transition from visual flight to increasingly greater dependence on instrument flight. What is perhaps of concern is that we do not know the answers to some of the current problems. We cannot even visualize all of the problems which will be facing the aircraft designer in the near future. Consequently, the emphasis of this chapter is on factors which affect the efficiency with which the pilot can get information from the internal environment of the aircraft. Some of these factors are: the way in which each instrument has been designed, the way the instruments are arranged in the cockpit, and the way the cockpit is illuminated.

DESIGN OF FLIGHT INSTRUMENTS

This discussion includes some of the psychological and visual factors that should be considered in the design of cockpit instruments and for the most part, this discussion is concerned with mechanical indicators in which there is movement of an indicating element; examples are the altimeter, the airspeed indicator, and the radio magnetic indicator. Some considerations are also given to radarscope presentations, although the major discussion of these displays is found in Chapter 15.

The modern aircraft cockpit contains an array of dials for instrument flight and navigation, power plant control, and monitoring of radio and other accessory equipment. Most of these instruments are classified as symbolic displays (see Fig. 13.1); they present an abstract representation of existing conditions by means of pointers and scales, or signal lights. Other cockpit instruments are classified as pictorial displays; they present a simplified simulation of the actual visual picture. Such indicators, best exemplified by the artificial horizon, are principally used to display information concerning spatial position.

Much research has been devoted to discovering the optimum design characteristics of symbolic displays for fast and precise interpretation. Such aspects as the size and design of scales, markings, pointers, letters, and numerals have been summarized in a number of publications[13-3,13-5,13-14] and are not reviewed here. The concern here is with the relative merits of symbolic and pictorial displays for flight control and navigation, the principles of pictorial display, and the integration and combination of interdependent information.

General Considerations

There is widespread agreement, supported by experimental evidence,[13-10] that instrument flight is considerably more difficult and demanding of the pilot than visual flight. In visual flight, most of the information required for controlling the flight of the aircraft can be obtained from the surrounding visual environment. In a diving turn, for example, the pilot sees a tilted visual field to show bank, the aircraft nose below horizon to show pitch, the movement of horizon and ground objects to show direction and rate of turn, and the increase in size of ground objects to show altitude change. It is true, however, that contact cues are deficient in some respects; several instruments are

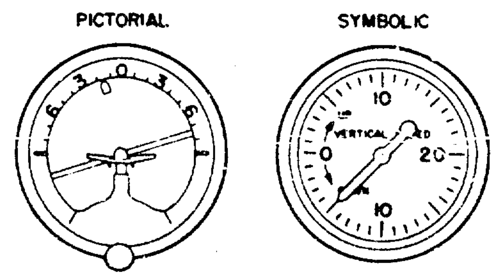


Figure 13.1 Basic Types of Flight Instruments

needed to main...n the accuracy required for flight. Visual flight might well be termed partial instrument flight, since it requires at least an airspeed indicator, altimeter, and some form of compass, in addition to ground reference.

In instrument flight, information concerning the attitude and position of the aircraft is presented as separate and discrete bits of information on the various indicators. This is probably the most important difference between visual and instrument flight. Adequate control of the aircraft under instrument conditions requires the pilot to integrate the information from all the critical instruments to determine what the aircraft is doing or is about to do. A changed indication on one instrument must be immediately and automatically associated with the corresponding changes on other instruments. If such an integrated conception is not achieved, the pilot is apt to "chase the dials," to scan one by one with a number of different aspects of the total situation in mind. As a result, there is a lack of precision; fluctuation occurs in the flight path due to over and under correction.[13-6] Thus, the pilot must handle a heavy information load in instrument flight.

Current instrument designs tend to increase the load on the pilot. Each instrument has been designed with little regard for the integration of the information it displays with the bits of information displayed by the other instruments on the panel. Although much effort has gone into improving the readability of individual instruments, the instruments are not complementary to each other. As a result, the pilot frequently must change his mental frame of reference to orientate himself to the particular display arrangement he is trying to interpret. As one investigator [13-21] has pointed out, "designing displays on an individual instrument basis can result in unnecessary burdening of the pilot by subjecting him to built-in sources of confusion in the cockpit." Some cited examples of possible sources of confusion are as follows:

1. Both the ID-250 RMI and a moving-pointer heading indicator have a compass rose and a pointer. On one the card is fixed, while on the other it moves. In one case, the pilot flies away from the pointer; in the other, he flies toward the pointer. The pointers are sensed oppositely for orientation purposes, since one is an aircraft reference display while the other is an earth reference display. The pilot is required to change his frame of reference when switching from one to the other.

2. Most panel instruments employ circular scales and a moving pointer element. The zero reference point may start at any position around the clock depending upon whether it is an altimeter, rate-of-climb, exhaust temperature, fuel flow, etc. Graduations vary from indicator to indicator, with some of the graduations being nonlinear.

Another way of evaluating current instruments is to examine them in terms of display-control relationships. In the final analysis, the information displayed on the instruments is used by the pilot in controlling the aircraft to follow a course, hold an attitude, make a power setting, etc. One study[13-20] has pointed out that, in order to do so, the pilot must receive information which tells him:

(1) When to move the controls

(2) Which control or controls to move

(3) Which direction to make the movements

(4) How much to move

(5) How long to move

This study also points out that one measure of the adequacy of a display is whether it provides information covering all five dimensions of control movement. A second measure is the number of intermediate variables which must be reckoned with, in using the instrument indication. The following are examples of ambiguous presentations of some instruments: 13-21

1. When flying inbound, on the ID-249 cross pointer, the pilot must remember that he flies toward the needles. When flying outbound, he flies away from the needles.

2. On the heading indicator and other fixed-scale indicators, pointer motion in terms of control action is reversed in the 180 degree sector. In the top half of the dial, a turn to the right results in

pointer movement to the right, while in the lower half the pointer appears to move to the left.

Such shortcomings as described above are relatively less critical in piloting aircraft travelling at relatively slow speeds. But the difficulty of the pilot's task is increased as aircraft performance goes up. Increased aircraft performance imposes more of a time stress in observing and interpreting instrument indications, and in planning and decision-making. In addition, increased performance capability requires the pilot to fly more precisely; at the same time, reductions in the number of crew members but additions to the number of crew functions have added to the job complexity.

There is widespread agreement that the expected advances in aircraft performance will soon make it impossible for the human operator to respond to information presented by current instruments so as to maneuver the aircraft adequately to fulfill its mission. A great deal of work has been devoted to improving present instruments as an interim solution, as well as to providing new concepts and display systems. In addition to the electronic and engineering advances upon which these developments are based, applied research on visual displays has also progressed. Some current approaches to the solution of the problem are reviewed here. Research concerned with improvement of standard instruments is presented below, followed by a discussion of more radical innovations in display system design.

Improvement of Standard Flight Instruments

Redesign of the Altitude Indicator. The conventional altimeter and similar multiple-pointer instruments have been found to be very difficult to read. The difficulty arises from the fact that the readings of three separate pointers on the altimeter must be combined in order to read out the desired information. A study [13-9] of instrument reading errors resulting in near accidents and nonfatal accidents found more reading errors of the altimeter than with any other single instrument. The most frequent error was that of reading the coarse scale indication (thousand- or ten-thousand foot scale) to the nearest number, rather than to the correct next lowest number. The pilot therefore thinks he has a thousand feet or more of altitude than is actually the case. The full seriousness of the situation is demonstrated by the results of a laboratory experiment [13-12] in which it was found that experienced Air Force pilots required 7.1 seconds to read all three hands of the instrument, with 11.7 percent of their readings in error by 1000 feet or more.

This study, conducted in 1947, compared the standard instrument with a number of alternative designs. Performance on the standard instrument and a counter-pointer design very similar to that first installed in production aircraft in 1954 is shown in Figure 13.2. A very long vertical scale moving behind a window and a repeating vertical scale were also found to be easy to read quantitatively, but were judged less desirable for check-reading and rate-observing than a moving pointer. When quantitative data are the only consideration, as is the case for the navigator, the results showed that a counter-type altimeter is best.

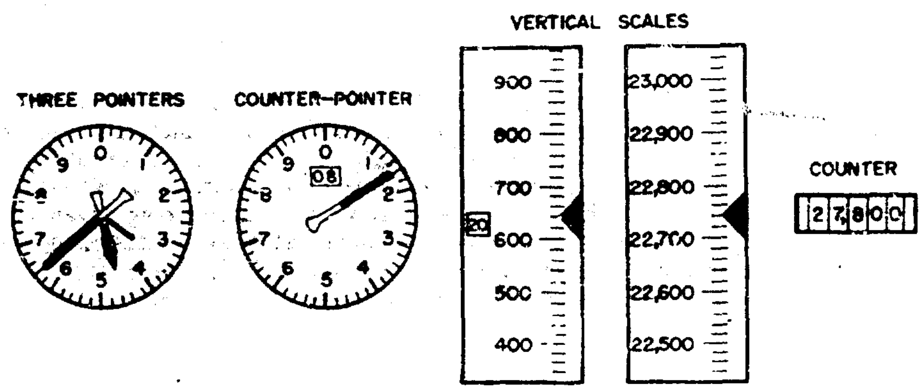
Earth Reference vs. Aircraft References in Flight Instruments

It is pointed out above that a pilot is often called upon to adapt a particular frame of reference in interpreting an instrument indication. In the case of instruments embodying pictorial elements to represent the aircraft's position in space (artificial horizon, ILS cross pointer, heading indicators, and experimental navigational displays), there are two different frames of references which may be employed.

Earth Reference. An earth reference display (see Fig. 13.3) is designed to simulate what the pilot sees when he is inside the aircraft looking out at the world. The display does not show the aircraft movements, but rather the change in the outside world that the pilot would see as a result of the aircraft movements. Thus, in the standard artificial horizon the miniature airplane is stationary while the horizon bar moves to simulate the actual horizon (see Fig. 13.1). This type of display is also called an "inside-out" display. It is also called a "fly-to" indicator, since a deviation from straight and level is corrected by flying toward the moving element or horizon bar.

Aircraft Reference. The aircraft reference indicator (see Fig. 13.3) is the alternative frame of reference that is employed. This type of display, also called an "outside-in" display, simulates what the pilot would see if outside the ... looking at the aircraft and the earth. In this case, the pilot

looks from a stationary vantage point (the earth), and the miniature airplane moves relative to the fixed environment. This is also called a "fly-from" indication, since the pilot flies from the indicating element to neutralize a deviation.



PERCENT ERRORS OF 1,000 FT. OR MORE	11.7	0.7	0.3	1.3	0.4
INTERPRETATION TIME IN SECONDS	7.1	1.7	2.3	1.7	0.0

Figure 13.2 Study in Altimeter Scales (from Grether [13-12])

It is apparent that the essential difference between the two types of reference indication is in terms of what the primary moving part of the display represents. In an earth reference display, the stationary portion of the display represents the aircraft; the pilot's control actions result in a reciprocal change of the moving part that represents some aspect of the stable external world. However, in an aircraft reference display, the moving element represents the aircraft, which changes in direct response to the control actions.

A number of experiments have demonstrated that there is a tendency to interpret the movement of an indicator as representing the movement of the aircraft. In the case of the standard artificial horizon, the pilot may respond to horizon bar movement as though it represented aircraft movement rather than the horizon. The result is that his control responses are reversed from what they should be in order to return the aircraft to the desired attitude. Several experiments [13-7, 13-8, 13-17] have shown that for subjects without previous instrument training, performance is better when using an instrument in which the airplane silhouette and not the horizon bar is the moving element. Moreover, an in-flight study [13-10] employing Air Force pilots with instrument experience showed that 7.5 percent initial reversal errors were made in recovering to straight and level flight employing the standard horizon. This demonstrates that such errors are not restricted to inexperienced personnel. A similar percentage of reversal errors found in a laboratory test [13-11] employing Air Force pilots with considerable instrument experience reinforces the conclusion that the standard earth-reference instrument may not be the best design for attitude indication.

A number of experiments with other instruments indicate the general superiority of the aircraft-reference type of display. A laboratory experiment [13-17] on localizer-glide path approach indicator design demonstrated that inexperienced subjects tested in a ground trainer are better able to keep the needle centered with a display in which the cross pointers represent the position of the aircraft rather than the earth. Another laboratory test [13-20] with experienced pilots showed that

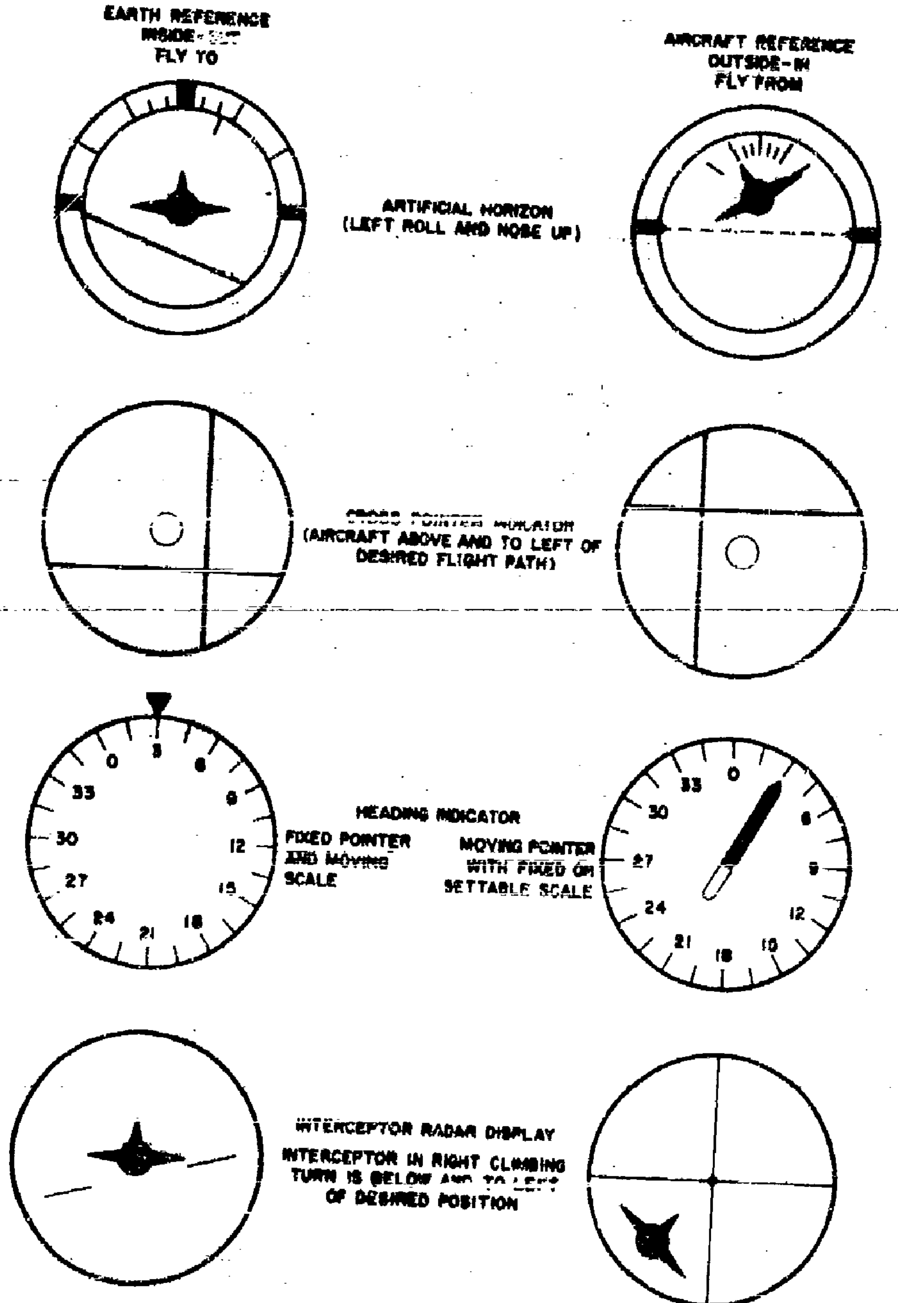


Figure 13.3 Earth Reference and Aircraft Reference Indicators

significantly fewer errors were made in solving typical navigation problems with a station-centered aircraft-reference display than with earth-reference displays in which the aircraft symbol is stationary and the station symbol moves. Results favoring the inside-out principle have been reported[13-18] for director-type interceptor steering displays.

The airplane-reference principle has not been firmly established as superior for all flight instruments. Experimental evidence is generally in favor of this type of display as easier to learn, to use, and to interpret. The explanation of this superiority, as advanced in the above report, is that "a pilot when flying contact perceives his airplane as moving against a fixed, stable outside world. If the world moves, he has vertigo. Apparently this same natural relationship should be preserved in the cockpit. Clearly the movement of a display index is its most compelling stimulus property and therefore it should represent the movement of the airplane against a fixed index representing the outside world." Many pilots prefer the earth-reference type of indicator. It should be pointed out that the current gyro horizon, the ILAS cross pointer, the flight path computer (zero reader), and the omnirange instruments are of the earth-reference type. The apparent reluctance to incorporate new experimental findings into the design of new instruments lies in the fear that such a change would cause difficulties for presently-trained pilots accustomed to current instruments. However, the report reveals that test pilots highly trained on a director-type steering display employing the earth-reference principle showed almost 100 percent transfer of training in switching to an experimental aircraft-reference display. Thus, it would appear that experienced pilots might have little difficulty transferring to an improved display design, but might have trouble transferring back and forth between old and new instrument designs.

An important consideration is that it is hazardous to mix aircraft-reference and earth-reference displays in a single instrument system so as to lead to built-in sources of confusion between alternative frames of reference. On the other hand, experienced pilots generally prefer the earth-reference type of instrument to the airplane-reference type. With the earth-reference type he is able to associate, from visual, vestibular, and gravitational cues, the movement of the fixed portion of the altitude indicator with his aircraft. With the airplane-reference type he cannot perform this natural association because the little airplane's rate of altitude change is twice that of the real aircraft. This may be the real reason that pilots dislike the airplane-reference type and not the fact that they were not trained with it. The presence of what has been regarded as experimental evidence that the airplane-reference type is better may be due to the fact that these vestibular and gravitational cues are negligible or absent in experimentation using simulators.

Combining Several Indications in a Single Instrument

One means of reducing the number of instruments crowding a panel is to present several kids of information in a single instrument. While saving panel space is a valuable goal, the major justification for the combination of several indications is that their joint presentation allows the operator to fixate the instrument more readily than if presented by two or more separate instruments. On the other hand, interpretation time is prolonged.

A combined instrument that has been sought for many years is one combining the directional gyro and artificial horizon indications for presenting pitch, bank, and azimuth information in a single display. A three-axis indicator giving attitude and heading throughout all-attitude maneuvers is under development by the Air Force.[13-21] A successful design of this type should prove of great value. Studies of eye movements under instrument flight conditions indicate that approximately 50 percent of the pilot's time is spent looking at the horizon and gyro-compass and that the greatest number of eye movements are between these two instruments.

An example of a combined instrument is the redesigned airspeed indicator for high performance aircraft in which the indicated airspeed and Mach numbers are combined. This design does away with the necessity of reading airspeed in knots from one indicator at slow speeds and then switching to another indicator for the Mach number at high speeds.

Another example of the combined instrument is the Bendix Flight Director System[13-1] in which two instruments replace four or more standard instruments. The Flight Path Indicator in this system is a plan position indicator that combines compass heading, omni-bearing selection, localizer or VOR indication, and glide slope indication. It is designed to replace the gyro-compass, omni-bearing selector, and ILS indicator. The second instrument in the system indicates aircraft

attitude in a conventional earth-reference display as well as steering commands, supplied by an associated computer, for localizer, range, and glide slope operations.

A study conducted in 1954[13-5] lists the ID-249 cross-pointer indicator (see Fig. 13.4) as illustrating another desirable type of combination. Here a pointer is used as a moving reference for alignment of a second pointer. This type of combination is most applicable when one indication is the first derivative of the other. In the ID-249 indicator, the localizer needle shows the aircraft position relative to the radio beam, while the relative heading pointer indicates the rate (first derivative) at which the aircraft approaches the desired flight path. If the relative heading indicator is kept aligned with the localizer needle, the aircraft approaches the desired track on an asymptotic path. Matching the pointer positions is an easier task than integrating two readings presented on separate indicators. The study points out that the success of such a combination depends upon a proper movement ratio between the two indicated values which must be determined for each application.

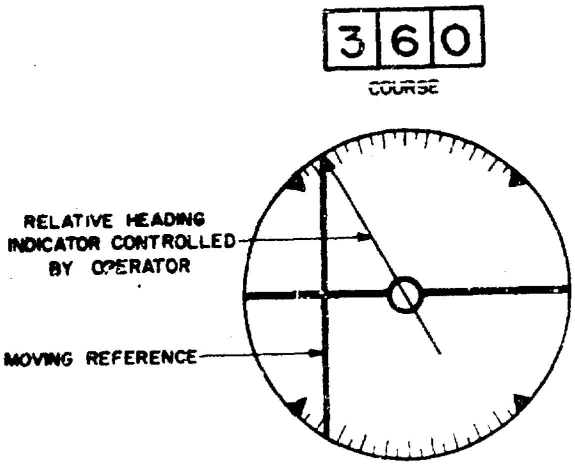


Figure 13.4 The ID-249 Cross-Pointer Indicator

The number of combined instrument designs has increased in the last few years and will very probably continue to do so as the increasing complexity of airborne equipment and ground control information put an additional premium on panel space. Job analyses of the pilots' tasks, eye movement studies, and data concerning the forms of information presentation which are most easily and efficiently interpreted can all contribute to this development. In each case, however, the challenge will be that of integrating several indications within a small area without making the interpretation of the desired information more difficult.

The combining of several types of information without regard for their essential and functional relationships will usually add to the difficulty of the operator's task. An example of an unsuccessful combination is the ID-314 "pin ball" indicator, a three-inch display with the capability of presenting 20 bits of information transmitted from the ground. Heading and attitude command information were combined with bombing, strafing, and other command information. One study[13-21] reports that most of these indicators are disconnected in operational aircraft. The greatest probability of success in combining information lies in choosing information closely interrelated in use or function, and combining it in a complementary form to allow their relationships to be more easily interpreted.

Integrated Instrument Display Systems

Our discussion thus far has been concerned with the improvement of existing instruments and the development of individual instruments for use in conventional panel display systems. In addition to these efforts, there are several research and development programs underway at the present time in which the design of the entire instrument panel is being developed on an integrated basis. In each case, visual communication requirements for flight control have been analyzed for a complete panel, rather than for an individual instrument. These developments are endeavoring to:

(1) Present related information in a single, unequivocal frame of reference for easier interpretability

(2) Combine related functions in a single display wherever possible

(3) Eliminate redundant instrumentation

These three goals are being investigated by a joint ONR-BuAer-Army instrument development program, a similar Air Force program under the direction of the Flight Control-Display Integrating Working Group at the Wright Air Development Center, and the instrument development program undertaken by the Hughes Aircraft Company. Two of the programs from which some information is available[13-2, 13-15, 13-16, 13-21] are described below. It should be emphasized that these proposed instrument display systems have not yet been adequately tested and evaluated. They are presented here for two reasons. First, they represent new approaches to instrument design, illustrating the changes in cockpit design that can be expected in the near future. Secondly, they employ very different techniques for reducing the multiplicity and complexity of panel displays.

The joint ONR-BuAer-Army long-range program[13-2] is expected to result in an instrument panel consisting of only two basic instruments instead of the 30 or more now in use.

Both would be cathode-ray tubes. One display would be semi-circular in shape and mounted vertically in front of the pilot as shown on Figure 13.5. It would use a flat transparent cathode-ray tube employing electrostatic principles to excite a phosphor screen sandwiched between glass plates. Its transparency would permit the pilot to see through the tube during visual flight. The second display, also a flat cathode-ray tube, would be mounted horizontally just inside the cockpit rim.

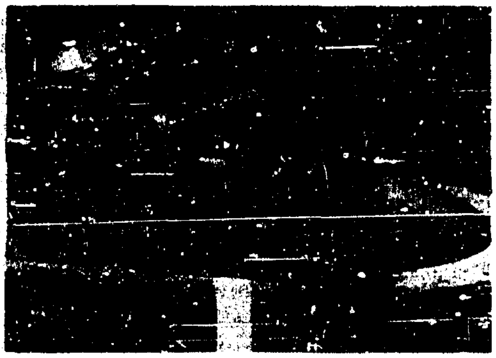


Figure 13.5 Mock-up of Aircraft Cockpit With Two Basic Cathode-Ray Tube Instruments

Both vertical display and circular display are flat TV tubes. Pilot heads stick in right hand and throttle in left. (see Alsher and Lazo[13-4])

The vertical display would be, essentially, a "forward-looking" display in which attitude, speed, and altitude of the aircraft would be shown together with a representation of physical obstacles such as mountains. It would be a pictorial display, simulating the visual world that the pilot would see if he were flying in clear weather. Visual cues employed in visual flight would be presented as flight information in the integrated display. However, a pictorial display designed to take advantage of the pilot's experience in looking out at the world in visual flight need not closely simulate visual flight conditions. It can be based instead on an abstract representation of the visual cues determined to be required for visual flight.

The horizontal display would also be a pictorial display, showing broad physical features of the earth below in a form similar to a radar map. This would be a "downward-looking" display encompassing the information required for navigation and traffic control.

Other necessary information, including quantitative data for navigation, fuel control, and power settings will either be shown by calibrations around the cathode-ray tube rims or displayed within the two screens. Six switches would be used to select the information required for specific flight phases.

The Air Force program at WADC[13-15,13-16,13-21] is based on an instrument panel design effort in which cockpit displays will be tailored to the specific mission of the aircraft. However, many of the instruments which make up the integrated display will be utilized in all types of aircraft. The proposed panel described below is for use in fighter-bomber types.

In analyzing instrument panel display requirements, cockpit instruments have been broken down into the following three general categories:

1. "Forward-looking" displays -- these include such indications as attitude, altitude, rate of climb, airspeed, g-load, Mach number, glide slope displacement, and director steering signals.

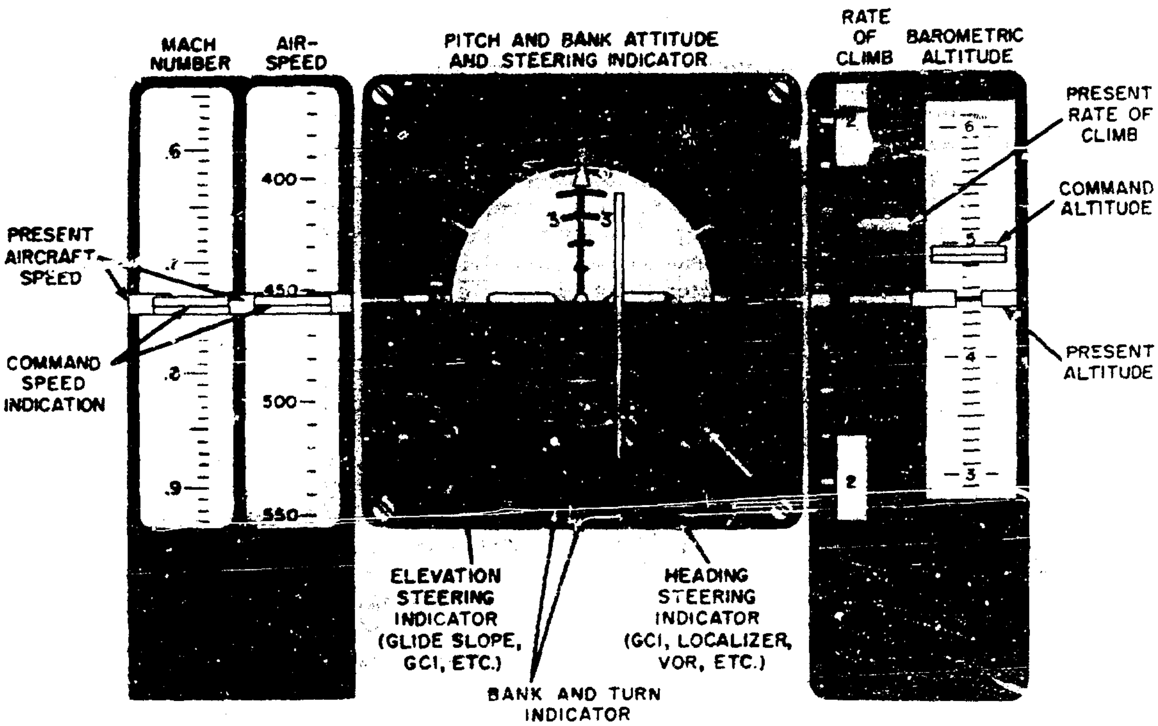
2. "Downward-looking" displays -- these include indications of heading, bearing, position relative to destination, target, and radio aids.

3. Power plant displays -- these include indications of rpm, thrust, temperature, oil pressure, optimum cruise settings, and fuel management data.

Let us examine first the configuration of "forward-looking" displays shown in Figure 13.6. In the center of the panel is a redesigned attitude indicator, which integrates pitch and roll information with flight director pitch and turn steering indications. Flight director command indications can be used for all mission phases, including takeoff, climb, cruise, weapon delivery, return to base, approach and landing. The design also includes needle and ball indications at the base of the instrument. Although several alternative configurations are being investigated, all employ the earth-reference display principle.

The altitude, rate-of-climb, airspeed, and Mach number displays represent a radical change in instrument configurations; they employ straight vertical scales rather than conventional circular scales. The altitude, airspeed, and Mach number displays employ moving tapes, thereby permitting expansion of the scale. Broken heavy white bars at the middle of each instrument serve as pointers indicating present performance. Command values, which can be set in manually or remotely, are shown by

heavy white center markers. The rate-of-climb indicator employs a moving pointer for rates up to 2000 ft/min; higher rates are shown by a moving tape in windows at the top or bottom of the scale. Other contemplated designs employing the same rectangular configuration would also provide terrain clearance and cabin pressure information, altitude steering signals, and angle of attack and g-load indications.



ADAPTED FROM AVIATION WEEK (JULY 23, 1956).
BY PERMISSION OF McGRAW-HILL PUBLISHING CO., INC.

Figure 13. 6 USAF Integrated Cockpit Display, Showing Mock-up of Pitch-Bank Axis Portion ("Forward Look") (after Klass 13-15)

The "forward-looking" portion of the panel is planned to provide a single frame of reference in interpreting instrument indications by providing a common center line that extends across all instruments in the row (see Fig. 13. 6). When the aircraft goes into a climb, for example, changes in all the rate and displacement indications (displayed side by side) are consistently related to the center reference line and to the pilot's control movement. Insofar as possible, scale displacements are in a single direction. Note also that actual performance data and desired performance values are displayed so that the pilot does not have to remember specific values. Instead, he flies the aircraft so as to keep the indices aligned across the reference line.

Navigation information formerly displayed on half a dozen instruments has been integrated into a single "downward-looking" display (see Fig. 13. 7). The display essentially combines the rotating-card presentation of the radio magnetic indicator with the vertical pointer of the ID-249 cross pointer indicator. Analysis showed that all navigational information requirements can be treated either as a displacement from a desired course or as a bearing relative to a fixed or moving known position. On this basis it was possible to develop a single display on which any navigation task could be presented as a triangulation problem.

Operation of the "downward-looking" display can be illustrated in terms of an instrument landing approach problem. The white course bar moves to show the position of the ILS localizer beam relative to the aircraft, which is shown as a stationary miniature at the center of the display. As the aircraft approaches the localizer beam, the white bar moves down toward the aircraft symbol, and then it lines up along the fore-aft axis of the aircraft symbol when the airplane is on the beam. Lateral displacement of the aircraft from the beam will then result in a movement of the bar to the right or left.

Note that the display principle employed in this instrument is consistent with that of the attitude indicator, in that they both employ the earth-reference principle.

Figure 13.8 shows the position of the "downward-looking" navigation display relative to the "forward-looking" display. This arrangement is planned to give a vertical line relationship passing from the fore-aft axis of the miniature airplane and RMI indication up through the needle and ball indication and the turn-steering pointer on the attitude indicator. Power plant displays (not shown here) will in most cases be rectangular, moving scale displays employing the horizontal reference line technique to facilitate check-reading.

We can now examine the differences in fundamental approach to the problem of integrated instrument system design exemplified in the two experimental programs described. The joint ONR-BuAer-Army effort is an attempt to produce a predominantly pictorial display, synthetically reproducing the visual cues of major importance for adequate aircraft control under visual flight conditions. Symbolic elements or indications are kept to a minimum. They are employed only where the more "natural" cues are judged to be inadequate or impossible to display pictorially. The result is two basic displays in which most of the information is displayed in terms of a single, "natural" frame of reference.

The proposed Air Force display system, on the other hand, uses a preponderance of individual symbolic displays. Some pictorial elements are utilized in the attitude indicator and navigational display. The chief concern in this case is upon finding consistent frames of reference for displaying bits of information in the individual instruments. In this case, the frames of reference employed are logical coding techniques based on the analysis of the inter-relationships among these bits of information and their relationship to the control movement of the operator. Some reduction in the number of individual instruments has been achieved through the integration of related information into single displays.

ADAPTED FROM AVIATION WEEK (JULY 30, 1956), BY PERMISSION OF McGRAW-HILL PUBLISHING CO., INC.

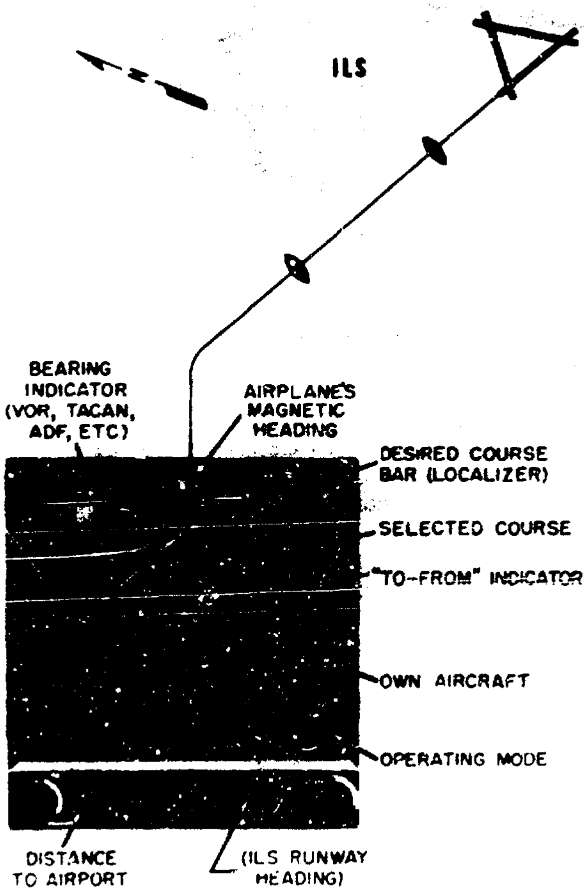
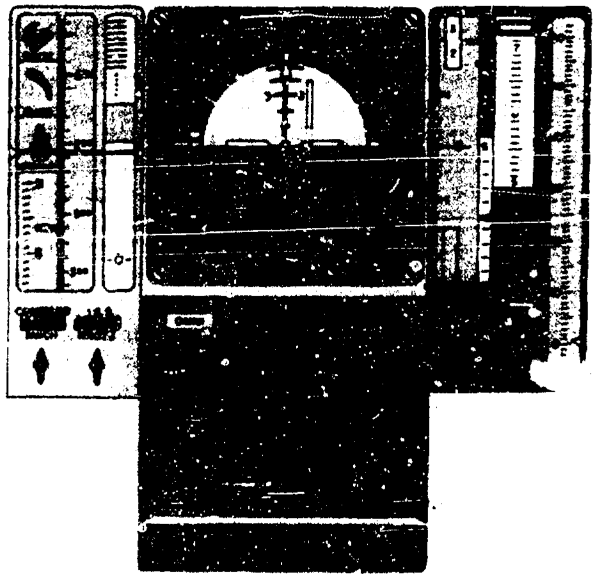


Figure 13.7 New USAF Downward-Looking Instrument. Note the Large Amount of Information it Displays. (after Klass[13-16])



ADAPTED FROM AVIATION WEEK (JULY 30, 1956), BY PERMISSION OF McGRAW-HILL PUBLISHING CO., INC.

Figure 13.8 USAF Panel Layout Which Integrates Horizontal and Vertical Lines of Reference (after Klass[13-16])

Pictorial vs Symbolic Instrument Display Systems

One investigator 13-13 has provided a valuable discussion of the relative merits of pictorial and symbolic types of instruments for displaying information for flight control. He points out that there are three types of reading functions served by flight instruments:

1. Check reading -- for assurance of a normal or desired indication

2. Qualitative reading -- for the meaning of a deviation from a normal or desired indication

3. Quantitative reading -- for the exact scale value

Symbolic instruments can serve all three types of reading function. However, pictorial displays require supplementary symbolic indications for quantitative reading, since the picture available in visual flight is itself deficient in quantitative information. The most successful pictorial display will probably be a skeletonized picture including a scale or other means of presenting quantitative data.

It is probably more economical and efficient to present data in the language and number symbols which the pilot customarily uses in his thought processes, rather than in a picture. On the other hand, symbols are substitutes for the real thing and, as such, depend upon training for their proper use. Pictorial displays might therefore be expected to require less training, be more easily interpreted, and give rise to fewer interpretation errors. These benefits may be expected from successful pictorial displays presenting such information as attitude, rate of turn, geographical position, and landing cues; it is these indications which are supplied to the pilot more successfully by direct vision than by existing instruments.

The above investigator lists the many visual qualities which would have to be simulated in a pictorial display in order to achieve complete realism. He points out the difficulties involved and the dangers of false interpretations arising from incomplete simulation of all important visual cues. From this standpoint, it is apparent that the important practical questions relating to the design of predominantly pictorial instruments and instrument systems are the following:

1. Is our knowledge of visual cues employed in visual flight complete enough?

2. Are instrumentation techniques adequate to present a synthetic picture of the visual world without serious losses in ease of interpretation, relative absence of ambiguity of interpretability, and saving in special instrument training?

3. Can the required precision of flight control be achieved by the addition of symbolic indications or by other techniques to the display without loss of the advantages of pictorial displays?

For symbolic displays, the equivalent question is: Can instrument systems, which are predominantly symbolic, be devised to make flight and landing operations as easy to carry out by instruments as by visual flight? The inadequacies of present symbolic instruments can be improved by achieving:

a. Consistency in direction of pointer movement

b. Combination of interdependent information

c. Differentiation among indications by position or coding

d. Standardization of instrument arrangement

e. Standardization of scale graduation intervals

Systems Considerations in Display Design

Aircraft panel instruments exist as a means of integrating the human pilot into the aircraft control system. They are used to present the information necessary to include him into the system as a sensing, decision-making, and control-actuating component. Control systems in which he

operates have changed markedly in the past fifteen years; the change has been toward the elaboration of automatic devices, electronic equipment, and computers to aid or replace the pilot. It is often said that the human operator's days in high performance aircraft are numbered, and that the problem of utilizing future aircraft will be solved by completely replacing the pilot by automatic devices.

Such a viewpoint of eliminating the pilot does not take into account the unique abilities which the human operator can contribute. We have seen that he is capable of recognizing and discriminating among complex patterns of stimuli far more efficiently than any computer now available. More important is his decision-making ability. The human operator can utilize information from many different kinds of inputs, evaluate it quickly on the basis of past experience and training and come to a decision on a course of action appropriate to the immediate situation. Another attribute of the human operator is his flexibility, the capacity to perform different tasks concurrently, to use different sources of information for his responses or decisions, and to change his transfer functions to fit the requirements of the situation. Moreover, the human operator has the capacity to learn and, therefore, to improve his performance with instruction and practice. Finally, he is reliable, easy to maintain, and immune to jamming.

Although these unique abilities argue for his continued use in future aircraft, we can point out some limitations to his abilities which must be taken into consideration when deciding what functions shall be assigned to the human operator. Viewed as an information-transmitting device, the human operator has relatively low channel capacity and low bandwidth. He has difficulties in processing the information conveyed in current instrument displays. The human operator also appears to be relatively ineffective in performing complex mathematical computations. He does poorly when called upon to act as an integrator or differentiator; he performs far more effectively as a simple amplifier in translating instrument indications into control responses. Finally, the human operator is not well suited to long, repetitive, or dull tasks. In such situations, his performance suffers from the effects of fatigue and inattention.

Although our present knowledge of the human operator permits us to make general observations of his characteristics, there are not sufficient experimental data on basic capacities to design complex aircraft man-machine systems to utilize best the capacities of the human operator. Further research is needed to determine which tasks the human operator should perform and those that should be taken over by automatic devices.

Some general statements can be made concerning the function of the human operator as viewed from the systems design standpoint. The division of tasks between human operator and automatic devices should be planned to allow the man to exercise judgment and make decisions. In order to do so, he should be relieved of repetitive and tedious tasks, and those requiring a high information-transmission rate. His primary concerns should be the selection of tactics, the mode of system operation, and the monitoring of system performance. He should be provided with displays and controls which allow him to impart to the system the flexibility inherent within his own characteristics.

In order to integrate the human operator into the control system, displays should be designed to convey the information concerning the aircraft position and operation in the simplest, most easily interpretable form. However, the displays should not eliminate information needed for decision making and the monitoring of performance. For example, flight director systems which indicate only deviations from a preselected program do not provide any information by which the pilot can monitor actual aircraft performance. In situations where the human operator can serve only as a simple compensatory tracking device, an automatic system can probably accomplish the task more effectively. This releases the operator to monitor the automatic system performance, overriding it only when necessary.

Check List for Designer

One team [13-19] compiled the following list of characteristics of a good display:

1. It presents indications which are easily verbalized or visualized.

2. It can be read quickly.

3. It can be read as accurately as necessary, but no more accurately than required.

4. Changing or changed indication is easy to detect.

5. It provides information in an immediately usable form without requiring calculation or translation into other units.

6. It is free from error-producing features such as cause orientation-reversal on the artificial horizon and misreading of multi-revolution or multi-pointer dials.

7. It fosters the recognition of errors, so that they do not persist.

8. It tells the operator which control to use to change its reading.

9. It tells the operator in which direction to operate the control.

10. It tells the operator when, how much, and for how long to move the control.

11. It can be easily distinguished from other instruments.

12. It is not unnecessarily obtrusive.

13. It gives the operator current information with minimum lag.

14. It cannot be used if it is inoperative.

EFFECTS OF VIBRATION ON VISUAL PERFORMANCE

Aside from its annoying and fatiguing effects, vibration has been recognized to impair visual performance in reciprocating aircraft of all kinds, in jets when buffeting occurs, and especially in helicopters. While design is usually toward minimizing vibration at its source and damping its effects in the environment, a certain amount is often inevitable and must be tolerated. Table 13. 1 lists typical vibrations in some aircraft. When vibration cannot be avoided, its effects upon visual performance may be reduced by proper design of the visual displays and printed materials which must be viewed. However, effective design depends upon an understanding of how vibration influences vision.

Research on the effects of vibration on visual performance have taken two directions. On the one hand, the effects of certain kinds of vibration impressed upon the operator's body, through his feet or seat, have been explored. On the other hand, the effects of certain kinds of vibration in the visual field have been determined.

Early research on the effects of vibration imposed upon the body measured human sensitivity to vibration. [13-30] Subjects standing on a vibrating platform, as frequency and amplitude of vibration were increased, judged when the vibration became (1) "just noticeable," (2) "easily noticeable," (3) "troublesome," (4) "disagreeable" (injurious over long periods of time), and (5) "dangerous" (injurious over short periods of time). Similar studies have been conducted in the aircraft situation. [13-22, 13-24, 13-28, 13-29, 13-33] Figure 13. 9 presents average amplitude values for three judgments at representative frequencies. As frequency of vibration increases, the amplitude necessary to yield a given judgment decreases. The relation between frequency and amplitude is curvilinear. The data suggest that the judgments of discomfort were made on the basis of particular threshold velocities rather than amplitude.

After bodily sensitivity to vibration was measured and discomfort thresholds were determined, efforts were made to discover the physiological effects upon which judgments of discomfort are based. Tactual sensitivity, tremor, reflexes, reaction time, pulse rate, blood pressure, metabolism, and visual acuity were measured before, during, and after two-hour exposures to various combinations of frequency and amplitude of vibration. [13-23] Since the subjects sat on a vibrating platform and the body provided considerable damping, effects of vibration on visual acuity were related to head vibration rather than to platform vibration. Figure 13. 10 shows binocular visual acuity at various frequencies of head vibration for five subjects. At particular frequencies there appear to be resonance points at which acuity was most affected. The first point might be due to difficulty in fixating the vibrating test object. The remaining peaks may be due to the effects of complex

sympathetic vibrations produced at resonance in the musculature of the eye, compounded with the fundamental vibration of the test object. The results are clear in indicating that vibration of the body and test object impairs visual efficiency. The results do not, however, permit an evaluation of the effects of vibration in the visual field as opposed to those of vibration impressed directly upon the body.

Table 13.1 Vector Amplitudes of Vibration in Two- and Four- Engine Aircraft (compiled from reports of the various mfrs. 13-27, 13-31)

Model	PV-1		DC-3		B-307		L-49	
Location	Nose (Sta. 94 3/4)	Accumulator	Rear of cockpit	Nose	Cabin		Cabin Floor Front (Sta. 460)	Rear (Sta. 875)
Engine order			1st	27/16	1st	27/16	2nd	2nd
Engine speed rpm	Amplitude of vibration, in.							
1,600	0.0188	0.0350				0.0028	0.0020	0.0023
1,700	0.0170	0.0230	0.0005	0.0080			0.0016	0.0018
1,800	0.0140	0.0085	0.0012	0.0060	0.0038		0.0015	0.0025
1,900	0.0068	0.0080	0.0013	0.0030	0.0030	0.0057	0.0023	0.0025
2,000	0.0098	0.0050	0.0010	0.0075	0.0046		0.0068	0.0040
2,100	0.0088	0.0030	0.0007	0.0020	0.0054		0.0023	0.0023
2,200	0.0080	0.0025		0.0015	0.0059	0.0077	0.0015	0.0025
2,300	0.0068	0.0015		0.0015	0.0049	0.0078	0.0020	0.0026
2,400	0.0075	0.0023			0.0075	0.0043	0.0020	0.0025

In some operational situations it is entirely possible for seating, clothing, personal equipment and the body to damp vibration so that little if any gets as far as the eyeball. In addition, there are those instances in which an operator must monitor instruments on a vibrating machine while he is stationary. In such cases, the effects of vibration in the visual field alone become important.

First, let us consider the matter of sensitivity to vibration in the visual field. 13-26, 13-32

The results of a determination of the minimum amplitudes of vibration in the visual field which are just perceptible at various frequencies are shown in Figure 13.11. Stimuli were printed materials in six- and eight-point type viewed at a reading distance of 14 inches under 13.0 and 23.5 ft-L. (The amplitude threshold increases with frequency, and the average amplitude threshold is in the neighborhood of 0.0056 inch.) The threshold increased with decreasing brightness, but the type size variable was not found to affect the threshold through the range tested. Visual thresholds to vibration related to discomfort thresholds are shown in Figure 13.12.

But what are the effects of surpra-threshold vibration in the visual field upon visual performance? In the aircraft situation one critical requirement is reading of printed materials: instrument faces, tables, charts, etc. In a series of studies, 13-25 subjects have performed simple mental arithmetic on printed numbers. The effect on the subjects' speed and accuracy has been measured as vibration was varied in frequency, amplitude and form, and as the printed material was varied in brightness, contrast and type size. Of these variables, amplitude of vibration, brightness and type size seem to be the most critical. The results of experiments on these variables are summarized in Figures 13.13 and 13.14 for a mid-frequency value of 1050 cpm. They show how the three variables interact to

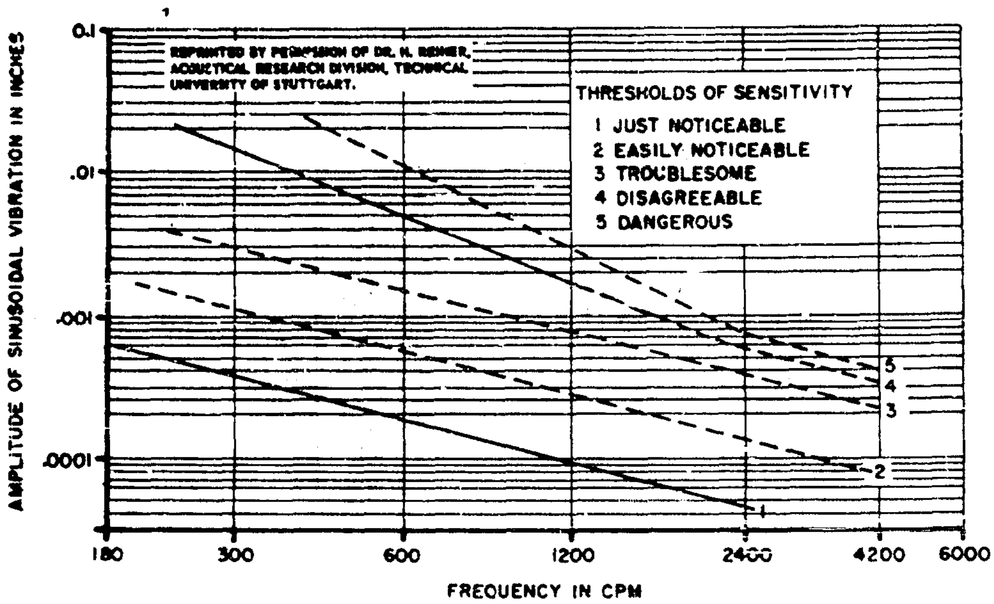


Figure 13.9 Thresholds of Sensitivity to Vibration

Vector amplitude and frequency are plotted for five degrees of comfort as parameters. The data were obtained with trained subjects standing on a vibrating platform. (from Reiher and Meister[13-30])

produce given decrements in speed and accuracy of performance. The authors [13-25] conclude:

"On a numeral-reading task involving simple mental arithmetic, performance is not significantly impaired by decrease of brightness to 0.05 ft-L, decrease of type size to 6-point or below, or increase of amplitude of visual vibration produced by rotating prisms at 1050 cpm to 0.02 inch, if only one factor is varied at a time.

"Two of these values, in combination, impair time scores from 0 to 40 percent and error scores from 0 to 190 percent. All three, in combination, impair time and error scores 130 and 1100 percent, respectively.

"Certainly for brightness, and possibly for type size, the range within which performance is not affected is broader than for reading of verbal material.

"Performance as a function of any one variable, especially when all other conditions are favorable, tends to improve rapidly to a critical value and then levels off sharply.

"Impairment caused by the visual vibration introduced by means of prisms is considerably less than would be caused by vibration of the head at the same amplitude, to judge from previous work on the relation of head vibration to acuity.

"Because of this factor and the possible interaction of various other unfavorable conditions, the results of these experiments should be considered as indicating the minimum impairments that would probably be produced in the most similar practical situation.

"Though the effect of head vibration can be assumed to be greater than that of exclusively visual vibration, for the same amplitude of relative vibratory movement, in some operational situations the visual vibration might be the more troublesome, because vibration of the viewing surfaces would cause excessive amplitudes of relative movement. For this reason separate estimates of the two factors would be desirable in practical application.

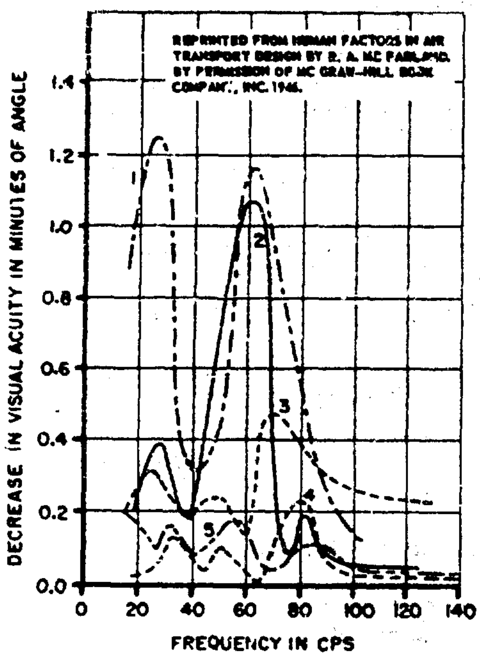


Figure 13.10 The Influence of Exposure to Vibration on Visual Acuity

The curves show that during 2 hrs. of exposure to vibration visual acuity decreases, particularly at two distinct ranges of frequency. The five curves are for different subjects.

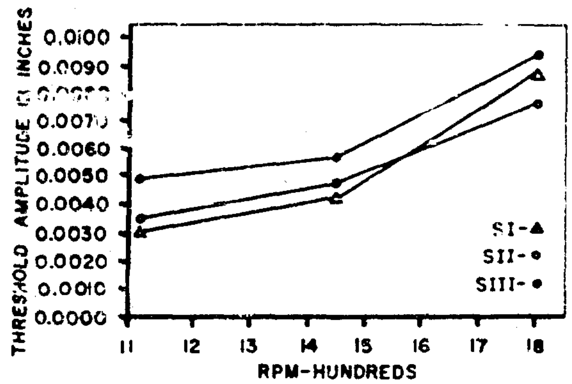


Figure 13.11 Amplitude Threshold at Three Frequencies for Three Subjects (First Order Interaction: Frequency X Subjects) (from Wulfeck[13-32])

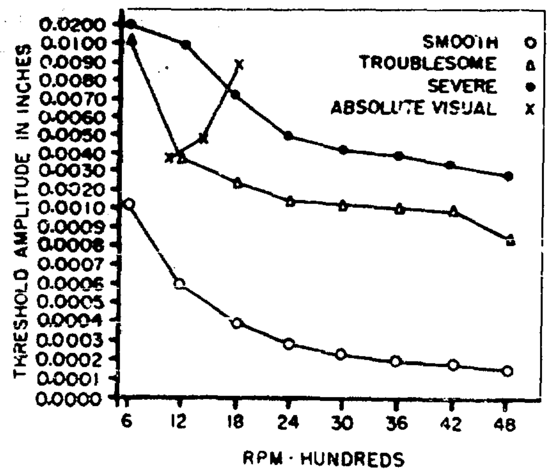


Figure 13.12 Amplitude Thresholds to Vibration: Bodily and Visual (from Wulfeck 13-32)

"As far as relative vibratory movement alone is concerned, under daylight or high levels of artifical illumination, the reading of printed numerical materials at 14 inches would not be affected by vibration amplitudes up to 0.02 inch nor of dial numerals by amplitudes up to 0.04 inch. Under night illumination designed to protect dark adaptation the tolerances would be much less. A drop in brightness to 0.046 ft-L, for example, puts a premium on printed numerals above 8-point in size, and brings the critical amplitude down to perhaps 0.01 inch for the larger type sizes; in the case of dials at the same brightness, the corresponding critical numeral size would be about 5/32 inch and the critical amplitude 0.02 inch; for 1/8-inch dial numerals a brightness drop to 0.2 ft-L would bring critical amplitude to 0.02 inch.

"Making due allowances for the difference in the scales, time and error scores appear to show about the same effects of the experimental conditions."

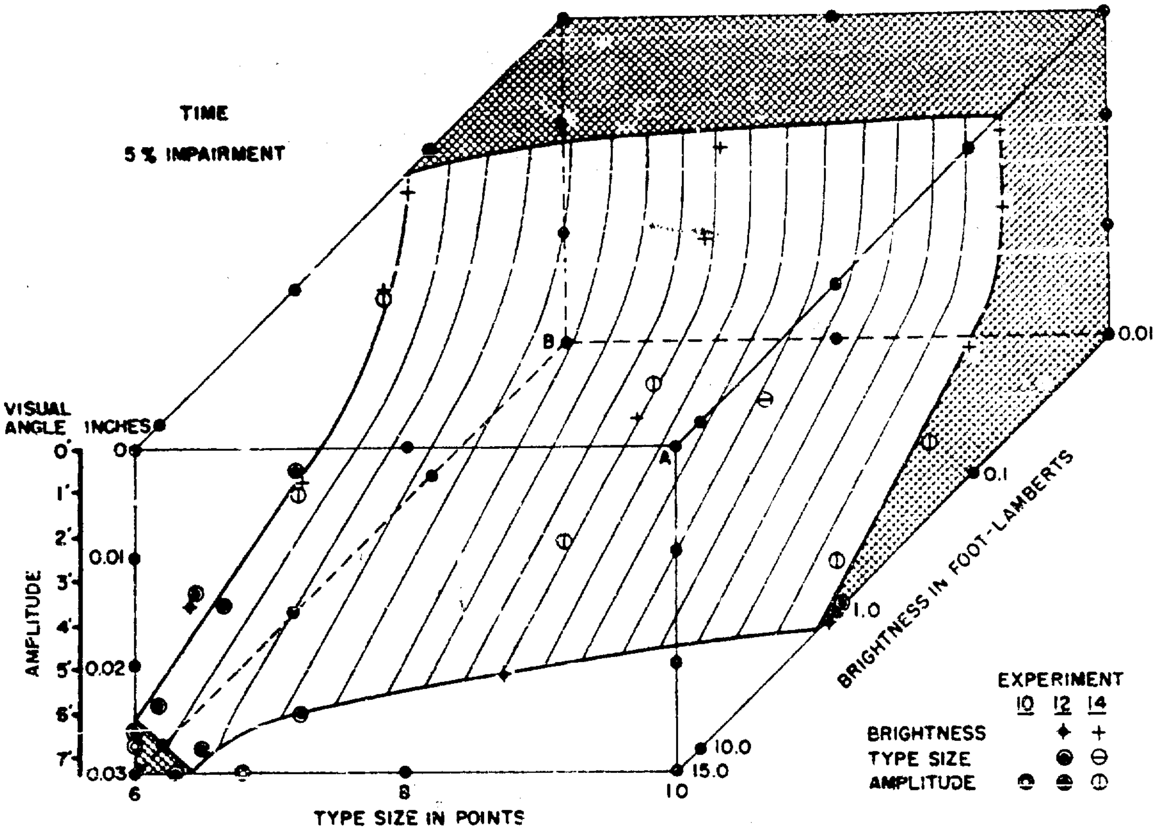


Figure 13. 13 Combinations of Amplitude, Brightness, and Type Size Producing a Constant Impairment in Time Scores

In the solid figure, corner A represents the ı ⁚ favorable conditions, B the least favorable. The curved surfac is the boundary at which time is increased 5% as condition ecome less favorable. Based on results from 12 subjects ε h in Experiments 10, 12, and 14. (from Crook et al. 13-)

These data, the data on visual thresholds to vibration, and the da on discomfort thresholds can be used to establish some general principles for avoiding or compe: ating for the effects of vibration in the visual field on visual performance. Maybe the most sig. ificant of these is that if brightness can be kept above 0. 1 ft-L, type size above 8-point, and vibration of material in the visual field less than that which would be judged "severe" (0. 0200 inch) anywhere in the frequency range if the body were subjected to it, there would be no impairment of legibility due to vibration. As a matter of fact, Figure 13. 14 shows that if amplitude is kept less "severe" for the body it will not even be visible.

If further research made it possible for us to determine the amount of vibration on the eyes resulting from vibration of the body, it would be possible for us also to establish general principles for offsetting the effects of vibration of the body on visual performance.

ARRANGEMENT OF INSTRUMENTS

In addition to providing optimum design characteristics for individual instruments, it is

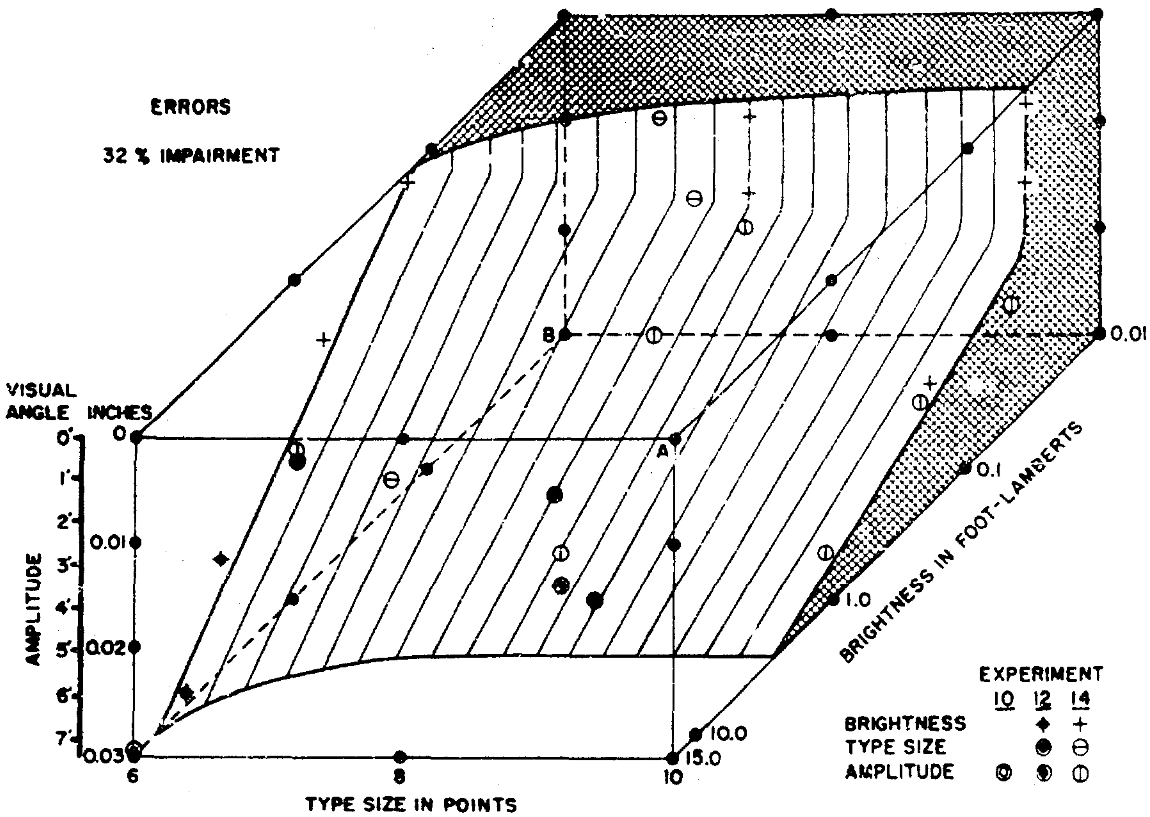


Figure 13. 14 Combinations of Amplitude, Brightness, and Type Size Producing a Constant Impairment in Error Scores

In the solid figure, corner A represents the most favorable conditions, B the least favorable. The curved surface is the boundary at which errors are increased 32% as conditions become less favorable. Based on results from 12 subjects each in Experiments 10, 12, and 14. (from Crook et al [13-25])

important that the location and arrangement of panel instruments is planned to simplify the pilots' task. The problem has two facets: The first is the determination of an optimum position and arrangement as determined from experimental data on the ease of recognition in various parts of the visual field, the relative frequency of use of various instruments, and the relative frequency of eye movements between different instruments. The second aspect is the standardization of panel layout so that the arrangement of instruments is consistent from one aircraft to another.

The proper grouping of instruments has its chief advantage in reducing the extent of eye movements in scanning the necessary instruments. Since more than 100 such eye movements per minute are made by the pilot under typical instrument flight conditions, decreasing the frequency and amplitude of eye movements serves to minimize ocular motor fatigue. Proper grouping reduces the time required to fixate and interpret the instruments, thereby reducing cockpit work load.

The standardization of instrument location is important to minimize the confusion and loss of efficiency which results when a pilot flies different types of aircraft or even models of the same

aircraft in which panel arrangements differ. The pressing need for standardization is illustrated by the finding that one type of aircraft requisitioned from the airlines during the Korean airlift had so many different panel configurations that flight crews required an extra hour or more of briefing on the particular cockpit they were to fly that day. 13-41 Similarly, another study 13-42 reported an airline pilot opinion survey which found that pilots considered the exact arrangement of instruments relatively unimportant as long as it was consistent from one aircraft to another. Although this shortcoming is less characteristic of military aircraft panel arrangements, practical considerations often require that deviations be made from the standard Air Force flight instrument configuration shown in Figure 13. 15.

The information which follows is based on experimental literature relating to these problems and examines the considerations involved in the utilization of these findings for present and future cockpit arrangements.

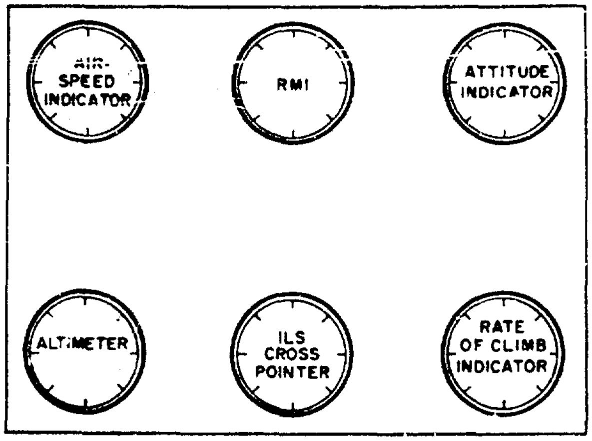


Figure 13. 15 Standard USAF Flight Instrument Panel Configuration

Direction of Eye Movements

The general finding on the direction of eye movements is that horizontal eye movements are more habitual and easier than vertical excursions. One team showed 13-36 that the eyes can look toward and recognize objects to the right and left of the initial fixation point more rapidly and easily than objects below. Performance was poorest for objects above. Another study 13-38 has shown that this directional relationship also holds when viewing an instrument panel; vertical eye movements were more difficult than horizontal.

Optimum Position

A study 13-47 of pilots' eye fixations while check-reading mock-ups of engine instrument panels revealed: (1) the top row of instruments is fixated more often than the bottom row, and (2) the top left sector of the panel is fixated more often than the top right. An in-flight study 13-44 comparing pilots' eye fixations with two different instrument arrangements showed differing amounts of time spent on an instrument depending upon its location. More time was spent on centrally located instruments regardless of what they were. The most frequently viewed positions on the panel were the top center and next, the lower center. We can conclude from these experiments that the most important or most frequently consulted instruments should be placed in a single row at the top of the panel directly before the pilot, with the most frequently scanned instrument in the center position. Following these, the next favorable position is the center of the second row.

Frequency of Use of Instruments

In order to utilize the findings of the studies 13-44, 13-47 of eye fixations, we need to know which instruments are most important, and should therefore be assigned the best positions on the panel. The results of a series of studies, 13-35, 13-37, 13-39, 13-40, 13-45, 13-46 in which a large amount of data was collected on the frequency, direction, and sequence of fixations of individual instruments, can be used in determining instrument priorities. These results were derived from the film records of pilots' eye movements in a variety of instrument flight conditions. Table 13. 2 summarizes some results from several of these studies, 13-37, 13-39, 13-45, 13-46 showing the proportion of time spent on each instrument during various maneuvers. Analyses in terms of average length of eye fixations of each instrument and number of fixations per minute showed essentially the same relationships. The data are particularly interesting in that they reflect the shifts in relative importance of the various instruments under varying flight conditions.

Table 13.2. Percentage of Eye Fixation Time Devoted to Individual Instruments Under Various Flight Conditions

Instrument	Straight and Level	Level Turn	Climb	Climb Turn	Descent	Descending Turn	ILAS Approach	GCA Approach
	Flight Condition							
Directional Gyro	37	26	20	23	21	24	25	49
Gyro Horizon	25	29	24	28	22	25	15	19
Airspeed	7	12	24	16	24	19	10	17
Altimeter	13	12	7	7	7	6	2	3
Rate of Climb	5	6	9	8	8	7	2	5
Turn and Bank	3	6	3	5	2	5	1	2
Engine Instruments	2	4	10	9	12	10	2	4
ILS cross pointer	-	-	-	-	-	-	41	-

The following conclusions can be drawn from the studies on which Table 13.2 is based:

1. The directional gyro, artificial horizon, and airspeed indicator were the most important instruments under all flight conditions, although dependence upon the altimeter increased in level flight. Generally, two-thirds of the pilots' time was spent on these three instruments.

2. The altimeter and rate-of-climb and turn-and-bank indicators were of secondary importance, with about 20 percent of the pilots' time devoted to them.

3. Engine instruments were rarely fixated in comparison to the flight instruments, averaging less than 10 percent. In fact, the values shown in the table overestimate the importance of the engine instruments. This is true because engine instrument fixations were generally twice as long (1.4 sec) as the flight instrument fixations, probably because of the greater necessity for quantitative reading of these instruments. They occupied the pilot's attention a significant portion (40 percent) of the time only during contact takeoffs.

4. In terms of frequency of eye movements between instruments, placement of the directional gyro in the center position was the optimum arrangement. Under almost all conditions, the greatest frequency of movements was between the directional gyro and the gyro horizon, closely followed by eye movements between the directional gyro and airspeed indicator.

5. The cross pointer instrument assumed primary importance on ILAS approaches, accounting for 41 percent of fixation time.

6. The airspeed indicator was apparently the only instrument consulted during visual landings, since pilots were found to be looking out of the cockpit 73 percent of the time and at the airspeed indicator 17 percent of the time.

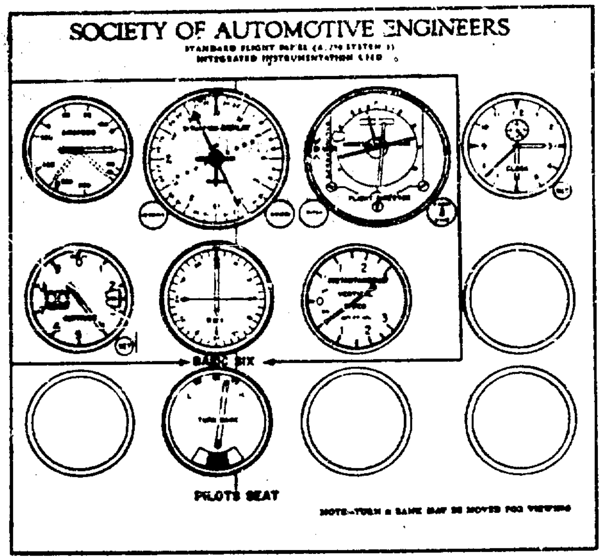
It can be seen that the standard Air Force flight panel arrangement (Fig. 13.15) is consistent with the findings on which Table 13.2 is based, since the three major instruments are placed in the upper row. With the radio magnetic indicator (equivalent to directional gyro) in the center position, the most frequent eye movements are short and horizontal. Placement of the cross pointer instrument in the center position of the bottom row is justified on the basis of the critical importance of this instrument in ILAS approaches.

Limiting Factors in Studies of Instrument Panels

Several factors which limit the usefulness of the results of the above studies should be mentioned here. First, there is the question of the influence of previous training upon instrument priorities. An experiment using a similar technique[13-43] studied the eye movements of Navy and Air Force pilots during routine instrument flight. It was found that the two groups emphasized different instruments. Air Force pilots watched the airspeed indicator more than the Navy pilots did, while experienced Navy pilots gave greater attention to the gyro horizon than the Air Force pilots did.

Secondly, it appears that the configuration employed in any test determines to some extent the relative use that each instrument will receive. This was demonstrated[13-35] in comparison tests between performance with the standard panel and that with an experimental configuration; significant differences in number of fixations of the altimeter and vertical speed and turn-and-bank indicators were found during some maneuvers.

Moreover, another limiting factor is that the tests were conducted in a C-45 aircraft. Caution is required before applying the data to high-performance aircraft, because of the differences in performance characteristics.



REPRINTED FROM AVIATION WEEK (SEPTEMBER 10, 1956).
BY PERMISSION OF McGRAW-HILL PUBLISHING CO., INC.

Figure 13.16 Standard Instrument Panel Arrangement for Transports, Developed by Cockpit Standardization Committee, Society of Automotive Engineers (from Klass[13-41])

Most important, the data for the studies were collected using a panel consisting of standard instruments. In the interim, a number of new integrated flight instruments have been developed. The standard instrument panel arrangement developed by the Cockpit Standardization Committee of the Society of Automotive Engineers, and required by Civil Air Regulations for integrated instrumentation installations in new transport aircraft, is shown in Figure 13.16. This configuration is based in part on the flight studies reviewed here, yet the instruments to be employed in several cases represent major changes from the standard instruments used in the original research. Additional experimentation is required to determine whether the basic findings reviewed here are applicable to integrated instruments incorporating flight director and other information, or to more radical innovations such as the experimental panel displays described earlier in the chapter.

Location of Other Instruments and Controls

All flight instruments other than the "basic six" should be grouped closely around the basic ones, preferably by extension of the horizontal rows. Engine instruments, controls, and radio equipment require only occasional visual attention and can therefore be situated farther away from the direct line of vision with less decrement in performance. The actual amount of displacement from the center depends, of course, on both the accuracy with which they must be seen or read, and the frequency of their use.

The most important (i.e., most frequently used) of the other displays and indicators which require visual attention are the engine instruments. They are located in the same plane of space as the flight instruments, in front of the pilot, because they must be read directly (quantitatively) as well as just check-read. However, since engine instruments are referred to less frequently, they are generally found either in a group off to the side of the panel or singly around the flight group, depending on the size of the cockpit. Because engine instruments are pointer-type indicators, they are not easily distinguishable from one another, as are the flight instruments. Their only differentiating characteristics are: (1) their labeling, e.g., rpm; and (2) the range and magnitude of their scales. This makes the pilot's task of discriminating between them a difficult one. Therefore, not only is standardization of their location as crucial as with the flight instruments, but also coding must be employed to further alleviate the situation.

What methods are there of coding engine instruments? One commonly used code is color,

but since red lighting is employed in the cockpit, this is not feasible. Shape coding may provide discriminable cues, but as yet, this has not been investigated. The other possibility is positioning, i.e., standardizing their location. This is more straightforward when the engine instruments are grouped together (all instruments associated with No. 1 engine placed in left-most position, those for No. 2 engine next, etc.). When engine instruments are not in a group, they should be arranged so that ones that look most similar are farthest apart.

Controls and warning lights should be situated according to their importance and frequency of use. Controls, for the most part, are best located near the display they affect and their manipulation should relate logically to the change that occurs on the display. An upward movement of a control lever should register an upward movement of the aircraft. Infrequently used controls or those with no associated displays and requiring no visual definition may be placed far to the sides of the cockpit. Warning lights should also be located near the associated controls or devices, and, most important, they must always be within the pilot's visual field when he is looking straight ahead. They should be located no more than seven inches to either side of the pilot's forward line of sight. 13-34

COCKPIT ILLUMINATION

An important general characteristic of the operator's workplace is lighting. How much, what color, and what kind of cockpit lighting should there be? To answer these questions, it is essential to know: (1) the kinds of visual tasks the operator is expected to perform inside and outside the aircraft, and the relations among them; and (2) the conditions external to the aircraft which will affect this ability to perform specific visual tasks both inside and outside the aircraft.

Operator Task Considerations

The fact that complete job or operational analyses of the visual tasks required of the operator (especially those outside the aircraft) have not been performed has led to practices which are often more theoretical than realistic. However, in the absence of complete specification of requirements for various missions, we can ask some obvious questions and consider the implications of them for cockpit or other station lighting. We can also identify some of the external conditions which will affect the operator's visual performance.

Does the operator ever have to look out of the aircraft to perform a critical task? In the case of some stations in current aircraft (and in many aircraft in the design stage) some operators do not need to see outside the aircraft. Even in extreme emergencies, being able to see outside the aircraft may not be necessary. Since external illumination can have no effect on the operator's state of adaptation in this case, no limit need be put on either brightness or wave length by any factors other than those which will maximize performance of his job inside the aircraft. Consider the bombardier's station or the radar countermeasure station, for example. When the primary task is monitoring a radar scope for detecting, identifying, and tracking targets on it, scope characteristics and the lighting of other instruments, as well as ambient illumination, can be designed for maximum performance independent of other considerations. The implication here is that each such station should be equipped with lighting specifically designed to maximize visual performance at that station. It may, therefore, be necessary to isolate each station from the illumination from other stations by curtaining or light partitions. In stations through which other members of the crew must pass, some means of protecting the adaptation of the transients should be provided. If the passage is short and unobstructed, reducing or extinguishing illumination in the station might be satisfactory. If passage through the station is difficult or if the transient operator must perform some visual task (e.g., checking a chart) with the regular occupant of the station, some auxiliary lighting may be needed. The auxiliary lighting should be as nearly compatible as possible with the adaptation requirements of each operator, and should be available for brief use in place of the regular lighting of the station.

Does the operator need to scan and detect objects intermittently against the night sky or against the ground at night while performing critical visual tasks within the aircraft? The requirement of some missions means that the eyes must be minimally sensitive one instant and be resolving fine detail the next. These conflicting requirements pose an almost classical problem in cockpit lighting. We know that the rods are more sensitive in a detection task than the cones and that maximum sensitivity of the rods is achieved by dark-adapting them. However, we also know that the cones are required for resolution of fine detail. When this conflict arises, the best lighting will employ the minimum brightness necessary for detailed tasks within the aircraft and hence permit

the rods to be as sensitive to low brightnesses as possible.

Light Intensity Considerations

How much light does an operator need to perform his tasks within the aircraft? Studies on several types of visual performance at low brightness levels seem to indicate that there is a critical level of white light below which performance rapidly deteriorates, and above which little if any improvement occurs. One of these studies 13-73 tested the subjects' ability to: (1) perceive motion, (2) judge depth, and (3) perform an addition task. For all of these tasks the critical level of illumination was between 0.05 and 0.10 foot-lamberts (ft-L). In another study 13-76 dial reading performance as a function of the brightness of the dial markings was investigated. The data indicated that both time and error scores increased rapidly at levels of illumination below 0.02-0.05 ft-L, and that performance above this level showed very little improvement. Another investigation 13-58 was concerned with the legibility of type (such as is used on aero charts) under low illuminations. The findings indicated that legibility falls off at an accelerated rate as the level of the illumination is reduced from 0.129 to 0.014 ft-L. In a more varied task situation, 13-75 that of flying different courses in a Link Trainer, similar results were obtained. The performance here improved as brightness was increased from 0.01 ft-L to 0.1 ft-L of illumination, and above this level there was no significant change. These data provide a good indication of the minimum amount of light that must be present in order for the pilot to perform his detailed visual tasks. However, even with these low levels of illumination, considerable loss of dark adaptation will occur, particularly in the periphery of the eye.

Color Considerations

What about the color (wave length) of light used for illumination? Several investigations 13-49, 13-59, 13-66 have been concerned with the effect that the wave length of the preceding light has on subsequent dark adaptation. In general, results indicate that, as the wave length of the light to which the eye is exposed increases, the time for the rods to recover their dark-adapted state decreases. Thus, as the color of the light goes from blue to green to yellow to orange to red, the dark-adapted condition of the rods is affected less and less. Several studies 13-57, 13-65 have compared the speed with which the rods recover their sensitivity after exposure to red light, and after exposure to white light. All of the studies report a significantly more rapid recovery after exposure to red light than after exposure to white light of a similar brightness. In one study 13-74 it was found that the effect of exposure to 58 millilamberts (mL) of red light on the rate of dark adaptation was approximately the same as exposure to one to two mL of white light. In another experiment, 13-65 speeds of dark adaptation after exposure to 26.3 mL of white and 38.9 mL of red light were compared. It took the eye about three times as long to recover from the white light exposure, despite the white light's lower brightness. A more applied study 13-53 in this area compared the effect on dark adaptation of two different colors of instrument panel lighting, low-color-temperature white vs. pure red. The results suggest a greater loss of dark adaptation occurring with the low-color-temperature-white lighting.

The data mentioned above bear mainly on the effect of wave length on subsequent rod threshold sensitivity. What is the differential effect of wave length on detailed visual cone performance? Several older studies 13-60, 13-61, 13-69 investigating the effects of colored illuminants in a variety of visual acuity and reading tasks gave conflicting results. Some of the task situations indicated that performance is favorably affected by red illumination; others showed that performance is adversely affected by any colored illuminant; and still others showed no differences in performance regardless of the color of illumination. From the present point of view, the results of some recent applied studies seem informative but they do not resolve the conflict. A review of the literature 13-80 concerning chart and map reading under different colored lighting reports that, regardless of color, the map surface must be lighted to a level of 0.046 ft-L in order that ordinary print be legible at a lap reading distance (15-18 inches). At this brightness level, green-yellow lighting raises the dark adaptation threshold about 0.6 log units, while the same level of red lighting raises the threshold only 0.3 log units. A return to the minimum threshold after exposure to the green-yellow lighting takes four to six minutes; after exposure to red lighting, one minute or less. A further advantage of red light is that its probability of detection from outside the aircraft is less then that of other wave lengths since it is most apt to stimulate only the rods of other observers.

One point about the red lighting of maps, brought out in two of the studies, 13-72, 13-80 is that the value of color coding of maps is lost if they are to be viewed under monochromatic light, since then the colors will change in appearance. If red light is used, red markings disappear, orange and brown markings become very difficult to see, green markings become grey, etc.

Dial reading performance as a function of the color of illumination has also been studied.13-77 The colors were selected from the red-orange-yellow end of the spectrum. They were yellow-green, yellow-orange, orange-red, and pure red, and were tested at two brightness levels, 0.01 and 0.1 ft-L. Performance at 0.01 ft-L was quite poor for all conditions. At the 0.1 ft-L level, performance in terms of accuracy was significantly better with deep red than with any of the other colors; time scores showed no differences as color was varied. These data were also compared with those from a dial-reading study using white light; performance under colored lighting was significantly better at both brightness levels. A generalized applied study 13-75 was conducted on experienced pilots flying instrument courses (either 32 minutes or 4 hours in length) in a Link Trainer. The courses were flown with four different colors illuminating the instrument panel: red, orange-red, orange-yellow and white. Three different brightness levels were used: 0.01, 0.1, and 1.0 ft-L. Performance improved as a function of increasing brightness up to the 0.1 brightness level; beyond this very little further improvement occurred. Performance was not affected differentially by the color of the light.

Combining the salient aspects of the data given on visual performance under different amounts and colors of illumination, a lighting system can be described that should be optimal for night flying when detection only is required. The intensity level should be approximately 0.1 ft-L and the color should be red (cut off at 640 $m\mu$), assuming the pilot needs to be dark-adapted.

Lighting System Considerations

What kind of lighting system should be employed? In one investigation,13-79 the effect on dark adaptation of indirect red and red floodlighting systems was compared under two conditions of extra-cockpit light: aircraft in completely dark hangar (i.e., no outside light) and aircraft in flight in clear moonless night sky with transient ground lights. Both kinds of lighting systems affected the absolute dark adaptation threshold, but not differentially; the increase in threshold in both cases was about 0.23 log units, which approximates the change found in the map reading experiment.13-80 It is possible that the loss is not operationally significant in some situations. Another study 13-55 on these two lighting systems has shown, however, that pilots prefer the indirect red over the red floodlighting by a large margin. The indirect red made for easier and more pleasant viewing of the instrument panel.

A further investigation 13-71 of pilots' preferences compared a red individual instrument (indirect) lighting system alone and in conjunction with a red floodlighting system. The individual lighting system was varied in brightness from 0.02 up to 1.15 ft-L and the floodlighting ranged from 0.02 up to 1.15 ft-L. Preferences were obtained both in a laboratory study using a cockpit mockup and in a field study in which pilots had flying experience with both lighting systems. In both situations, the results were the same -- the pilots stated that they found the floodlighting unnecessary. Also they reported no undesirable visual effects from the brightness contrast between the instrument dial faces and the surrounding panel areas when the indirect system was used alone. This can be attributed to the relatively large amount of light which spills over the dial face, thus providing a "built-in" system of contrast reduction.

A similar study 13-51 compared two lighting systems for consoles using transillumination alone and in conjunction with a red floodlighting system. In this laboratory study, the brightness of a panel of dials in a cockpit enclosure was varied from 0.015 up to 0.168 ft-L by transillumination. These brightness levels were tested alone, and with additional floodlighting ranging up to 0.042 foot-candle (ft-c). Two lighting conditions were considered most comfortable, 0.044 ft-L of transillumination with 0.025 ft-c of floodlighting, and 0.168 ft-L of transillumination alone. A second part of the study, employing a cockpit mockup in a planetarium, required pilots to select combinations of transillumination and floodlighting to meet the three different criteria: (1) minimum -- for barely legible conditions of the console markings; (2) normal -- for the dark-adapted pilot; and (3) maximum -- for the non-dark-adapted pilot flying at night. Most pilots first selected a transillumination level that would afford the best legibility of the panel for the particular criterion, and then selected a floodlighting level that would fill in the other cockpit areas to provide better general orientation. The transillumination levels chosen for the three criteria were: (1) minimum -- 0.068 ft-L,

(2) normal -- 0.111 ft-L, and (3) maximum -- 0.335 ft-L. Interestingly enough, the floodlighting levels chosen were about the same regardless of the criterion, about 0.042 ft-c. From these results, the authors 13-51 recommend an auxiliary floodlighting system that can be adjusted over the three brightness levels: (1) dim -- 0.05 ft-c as an aid to cockpit orientation; (2) medium -- 0.2 ft-c as an adequate lighting system alone for emergency use; and (3) bright -- 2.0 ft-c as an additional system when the pilot has been exposed to intense light. Floodlighting is needed as a supplement to the transillumination for cockpit orientation. Unlike the individual instrument lighting system, only a very small amount of light escapes beyond the plastic plates in transillumination.

A survey 13-52 of lighting preferences in a cockpit mockup situation further demonstrates (at least in a qualitative way) the need for a supplementary floodlighting system for consoles. The lighting systems investigated were indirect, floodlighting, or a combination of the two, and were tried on each of two cockpit areas, consoles and instrument panel. For the consoles, most pilots preferred a combined indirect and floodlighting system as opposed to either one alone. For the instrument panel, the pilots preferred the indirect lighting system alone.

Summarizing the data given above, it appears that when the task to be performed outside the aircraft depends upon detection of low brightnesses and not resolution of fine detail, the cockpit lighting systems should incorporate two separate features: (1) indirect red lighting for the instrument panel, and (2) an additional red floodlight for consoles and other recessed areas in which controls are situated.

Ultraviolet lighting is not desirable for cockpit illumination, because the most stable phosphors now available are chiefly yellow or yellow-green, which are not desirable wave lengths for night lighting. If stability is achieved for a red phosphor, ultraviolet lighting could be used in place of the system recommended above, provided that reflections are controlled and some red floodlighting is used to aid in general orientation. Another disadvantage of ultraviolet lighting is that it causes fluorescence of the eye lens, which reduces vision by causing haze.

Does the operator need to recognize and identify objects against the night sky or against the ground at night intermittently while performing critical visual tasks within the aircraft? The preceding discussion of this section has been based on a cockpit lighting system for use when the primary task to be performed outside the aircraft is detection. Often, however, the detection of objects is far from sufficient for many missions or emergency situations. High-performance aircraft, which are often the tactical or air-defense mission targets, move through great distances at extremely high speeds. High-performance bombers are reaching altitudes from which strategic targets, fixes, landmarks, certain terrain features, and even air strips are seen as minute. In many instances, therefore, it would seem as if the resolution of fine detail is critical for successful completion of the mission. As seen from the curves in Figure 13.17 of acuity versus retinal location, the resolution of fine detail, such as would be required in identifying a fast-moving aircraft, requires that the cones be used. If such resolution must be accomplished at night, the cones must be dark-adapted. In the preceding discussion it was pointed out that the cones do not seem to function at a brightness lower than approximately 0.003 ft-L, even if well adapted. It can be concluded that if the mission requires high acuity to resolve targets at a brightness appreciably lower than 0.003 ft-L, it should be done with the aid of radar. In such instances, the red lighting system just described would increase the probability of detection of gross detail; it should be used if compatible with the adaptation requirements of the radar.

When the brightness of the targets to be recognized can be expected to fall above 0.003 ft-L, the cones might be able to function if properly adapted, while the rods could not. Compared to the mass of research done to optimize lighting conditions for rod adaptation, little has been done to establish optimal conditions for cone adaptation. Probably the lack of data specifying the pilots' visual tasks accounts for the fact that recognition of the necessity for cone adaptation in some missions is not common. Furthermore, applications of the red light system or principle have been so indiscriminately made that many appear to accept red light as a universal solution to all adaptation problems. Consider, for instance, the radiologist who faithfully dons his red goggles for 30 minutes prior to a fluoroscopic examination during which he must resolve critical details such as fracture lines, etc. There is a good chance that some other lighting system may better facilitate cone adaptation and be more suitable for situations in which only maximum cone sensitivity is required. The luminance function (Fig. 13.18) shows that a filter transmitting only the red end of the spectrum (above approx. 640 mμ) permits vision with the cones while allowing the rods to adapt. By looking at the other end of the curves, it can be seen that a filter transmitting only blue would, at low illumination

levels, permit vision with the rods while allowing the cones to adapt. Unfortunately, not as much experimental basis exists for specifying blue lighting as for red lighting, but there are probably many situations which should use blue lighting for cone adaptation. It may be established through future research that the rods are sufficient for minimal acuity tasks such as the "reading" of specially redesigned dials in a cockpit illuminated with low-level blue light. If this happens, a blue lighting system may become desirable for the situation in which the operator needs to recognize and identify objects against the night sky intermittently while monitoring instruments within the cockpit.

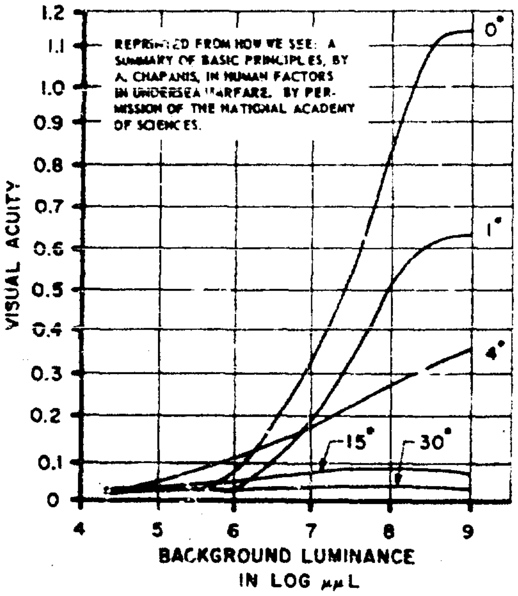


Figure 13.17 Visual Acuity as a Function of the Background Luminance of the Acuity Object at Various Retinal Locations (from Chapanis[13-54]) (see Mandelbaum and Rowland[13-70])

Light Contrast Problems

As compared to the night sky, the day sky presents the opposite of the light contrast problem. During the day, the brightness level of the outside sky is considerably higher than that of the cockpit interior. In terms of the pilot's tasks, what now is the major lighting problem? The kind of task that best illustrates this problem is when the pilot must be able to read his instruments immediately after performing an outside observation. The problem is one of maintaining the eyes at a relatively constant adaptation level by reducing the brightness differences between the two areas, thereby reducing the time during which the pilot is literally blinded as his eyes move from an area of high brightness to one of low brightness (from sky to instruments). Figure 13.19 shows dark adaptation as a function of the region of the retina stimulated. For daylight flying at relatively low altitudes (below 20,000 ft), the brightness problem is minimal; however, at high altitudes (above 30,000 ft) where many aircraft now fly, this problem is serious. The problem also exists when flying near lightning flashes or into the sun. In the case of high altitudes, two factors are involved; light is reflected from underlying clouds, and there are direct rays from the sun, but the sun is not much stronger than at low altitude on a clear day.

The general contrast problem is discussed in Chapter 8, and will receive only brief mention here. Numerous studies[13-48,13-56] have dealt with the problem of the brightness of the area that forms the background upon or within which the visual task is located. These studies indicate that both visual performance and visual comfort are best when the brightness of the general background is about the same as the brightness of the task area. In any case, the outer areas should have a brightness between one-tenth to three times that of the task area. The nearer all areas approach unity in their brightness ratios, the better is the visibility and the less the distraction from glare, which eventually produces fatigue.

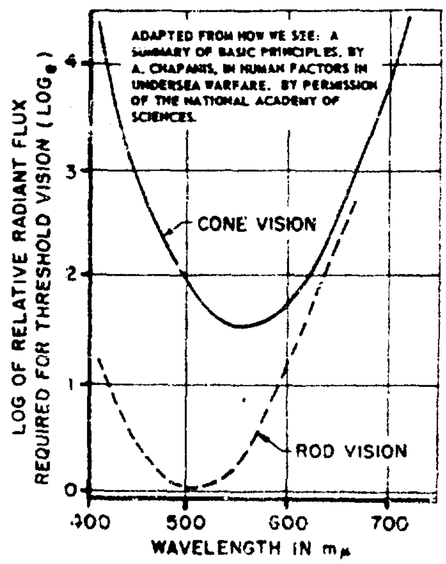


Figure 13.18 Spectral Sensitivity Curve. Relative Amounts of Radiant Flux Required to Stimulate the Rods and Cones. (after Chapanis[13-54])

The applied studies dealing specifically with the aircraft problems have been mainly concerned with the color of cockpit interiors.

One field study[13-62] made during both day and night flights, compared a gray cockpit interior and instrument panel with the conventional black. Each pilot was presented with a questionnaire designed to evaluate the interiors and panels in terms of functional suitability, visual adaptation and general appearance. The results indicate an overwhelming preference for the gray interior and panel.

Another in-flight evaluation[13-68] conducted during both day and night conditions, had two aims: (1) to determine the preferred reflectability of cockpit paint, and (2) to use this value in determining the preferred color. For the first determination, the pilots selected from a series of five colors (light gray through black), a gray that they thought most suitable for the cockpit interior in different flight situations. The most preferred shade was about 22 percent reflective. Then, for the second determination, the pilots selected from a series of five colors (light green, light blue, neutral, dark gull-gray, all 22 percent reflective, and standard black), a hue that they thought best for different flight situations. The majority of preferences were for the dark gull-gray; however, some preferred the lighter paints for night operations. In general, pilots prefer neutral paints that are not more than 23 percent reflective. These paints provide an increased brightness level in the cockpit during day flights by reflecting light into recessed areas; and they reduce the contrast between the interior and exterior of the cockpit, which is especially important at high altitudes.

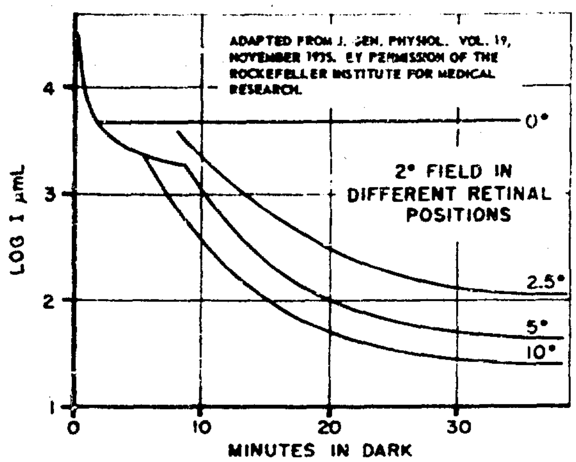


Figure 13.19 Dark Adaptation as Function of the Region of the Retina Stimulated

Dark adaptation curves measured with a 2-degree test object placed at various angular distances from the fixation point. (from Stevens [13-78], Fig. 18, p. 947) (data from Hecht, Haig & Wald)

One study[13-50] evaluated a light green cockpit interior during both day and night flight at altitudes over 40,000 feet. The results are again qualitative, but they indicate that the pilots preferred light green to the conventional black. The two reasons given were: (1) daylight visibility for all instruments, controls, etc., within the cockpit was considerably improved; and (2) reflections that occurred during night flight were eliminated. In this study an evaluation was also made of floodlighting, both to improve the visibility of recessed consoles when flying at high altitudes, and to minimize the blinding effect of lightning flashes. The results indicate that in both situations the floodlighting is essential; pilots were blinded from three to six minutes by a lightning flash in a darkened plane, and only 15 to 30 seconds in a brightly lighted plane. Some research[13-62,13-63,13-64] indicates the loss in sensitivity which can occur as a result of exposure to brief flashes of light.

Part of a study[13-50] evaluated the use of polarized goggles when making a visual search in the vicinity of the sun. In general, vision was considerably improved when the dark position of the goggles was used for the outside search and the clear position used to view the cockpit interior.

Summarizing all of the aspects of the aircraft lighting problem, a final integrated system emerges; it should include:

1. A neutral-colored cockpit interior and instrument panel

2. An indirect red lighting system for the instrument panel, with the possibility after more research of using a blue lighting system when cone adaptation only is required

3. An additional red floodlighting system for recessed consoles and general cockpit orientation

4. A white floodlighting system for use when near lightning flashes or other areas of very high intensity

Simulated Blind Flying Problems

The function of airborne simulated blind flying equipment should be to enable the pilot to practice instrument flight without the distraction of external cues. One wants good blackout of the horizon and good visibility of the instruments. Four systems have been tested: (1) Two-stage system, employing two antagonistic transparent light filters for selective vision, (2) Hood system, where continuous opaque surfaces are presented to occlude certain areas, (3) Louver system, where successive slats project from windows, and (4) Single-stage system, employing one sharp cut-off filter, matched in spectral characteristics with an artificial light source.

The two-stage system is the most satisfactory of the four general systems described above and is most effective for general use in all aircraft types and in a variety of training situations. The principle involved is a simple one - if white light from a single light source is passed through two filters in succession, only those wave lengths common to both filters will be transmitted. In the two-stage system, the instructor, on whom the safety of the plane depends, looks through panels of amber so that his view outside the aircraft is occluded. The chief limitation of this "best" system is that the safety pilot's vision may be reduced dangerously at low external brightnesses. Secondarily, pilots dislike goggles in any system. Thirdly, auxiliary lighting is sometimes required in order that the instruments shall be sufficiently visible to the goggled pilot.

DESIGN OF FLIGHT INSTRUMENTS

13-1 Anon. The Bendix Flight Director System. Eclipse-Pioneer Div., Bendix Aviation Corp., Teterboro, N. J. Publication No. 583 [illegible].

13-2 Anon. Flat TV Tubes for Instrument Flying. Research Reviews. Office of Naval Research, Washington, D. C. February 1956. pp. 13-15.

13-3 Anon. Handbook of Human Engineering Data. Office of Naval Research, Special Devices Center. Nav Exos P-643 (Tufts College).

13-4 Alsher, D., and Lazo, J., A Study of the Requirements for Background Lighting of Aircraft Instruments and Lucite Illuminated Consoles. Part 3. Investigations in the Floodlighting of Transilluminated Cockpit Displays. Report TED NAM EL-60[illegible]. U. S. Naval Air Experimental Station, Philadelphia, Pa. October 17, 1951.

13-5 Baker, C. A., and Grether, W. F., Visual Presentation of Information. WADC Tech. Report 54-160. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. August 1954.

13-6 Bartlett, F. C., Fatigue in the Air Pilot. Great Britain. Air Ministry. FPRC-488. August [illegible]

13-7 Browne, R. C., Comparative Trials of Two Attitude Indicators. Great Britain. Air Ministry. FPRC [illegible]11(a). April 1945. p. 5.

13-8 Browne, R. C., Comparative Trials of Two Attitude Indicators: Preliminary Note. Great Britain. Air Ministry. FPRC [illegible]. [illegible] p. 6.

13-9 Fitts, P. M., and Jones R. E., Psychological Aspects of Instrument Display. I. Analysis of 270 "Pilot-Error" Experiences in Reading and Interpreting Aircraft Instruments. Report No. TSEAA-694-12A. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. October 1, 1947. p. 47.

13-10 Fitts, P. M., Jones, R. E., Milton, J. L., and Morris, J. B., Pilot Reaction Time: A Study of the Time Required by Pilots to Comprehend and React to "Contact and Instrument" Recovery Problems. Memorandum Report No. TSEAA-694-13. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. May 2, 1947. p. 12.

13-11 Gardner, J. F., Speed and Accuracy of Response to Five Different Attitude Indicators. WADC Tech. Report 54-236. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. December 1954. p. 22.

13-12 Grether, W. F., The Effect of Variations in Indicator Design upon Speed and Accuracy of Altitude Readings. TSEAA-694-14. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. September 2, 1947. p. 19.

13-13 Grether, W. F., Discussion of Pictorial Versus Symbolic Aircraft Instrument Displays. TSEAA-694-2B. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. August 4, 1947. p. 19.

13-14 Kappauf, W. E., Studies Pertaining to the Design of Visual Displays for Aircraft Instruments, Computers, Maps, Charts, Tables, and Graphs: A Review of Literature. AF Tech. Report 5765. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. April 1949.

13-15 Klass, P. J., "Instrument Design. Part I: USAF Reveals New Instrument Concept." Aviation Week. Vol. 65. No. 4. July 23, 1956. pp. 62-67.

DESIGN OF FLIGHT INSTRUMENTS (Cont)

13-16 Klass, P. J., "Instrument Design. Part II: USAF Goal: More Data, Fewer Instruments." Aviation Week. Vol. 65. No. 5. July 30, 1956. pp. 48-56.

13-17 Loucks, R. B., An Experimental Study of the Effectiveness with Which Novices Can Interpret a Localizer-Glide Path Approach Indicator. USAF Tech. Report 5959. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. October 1949. p. 14.

13-18 Roscoe, S. N., "Designing the Cockpit for High-Speed Flight." Aero. Engrg. Rev. Vol. 13. No. 12. December 1954.

13-19 Sanders, V. L., and Cohen, J., The Influence of Methodology on Research on Instrument Displays. WADC Tech. Report 53-93. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. 1953.

13-20 Williams, A. C., Jr., Analysis of Information Required for Instrument Flight. Special Devices Center, Office of Naval Research, Port Washington, N. Y. Project, 20-L-1. [illegible] Report. p. 15.

13-21 Wright, L. C., The Air Force Flight Control and Flight Display Integration Program (A Progress Report of One Aspect of the Program). Updated Transcript of Presentation to Wright Air Development Center Management and Laboratory Personnel on February 28, 1956.

EFFECTS OF VIBRATION ON VISUAL PERFORMANCE

13-22 Bust, S. G., "Propeller Balance Problems." Journal S.A.E. (Trans.). Vol. 53 (11). 1945. pp. 646-655.

13-23 Coermann, R., "Untersuchungen über die Einwirkung von Schwingungen auf den menschlichen Organismus." (Investigations of the Effect of Vibrations on the Human Organism). Jahrb. der deut. Luftfahrtforschung. Part 3. 1938. pp. 111-142.

13-24 Crossman, H., "Aircraft Vibration." [illegible] 1932. pp. 200-250.

13-25 Crook, M. N., Harker, G. S., Hoffman, A. C., and [illegible] of Amplitude of Apparent Vibration, Brightness, and Type Size [illegible] Tech. Report No. 6246. Wright Air Development Center, Wright-Patterson Air Force Base. September 1950.

13-26 Crook, M. N., Harker, G. S., Hoffman, A. C., [illegible] W., and Kennedy, J. L., A Determination of Amplitude Thresholds for the Visual Perception of Vibration. U. S. Air Force, Air Materiel Command. USAF Memorandum Report No. MCREXD-694-1R. February 1949.

13-27 Dickie, J. A., Vibration Isolation of Pilot - Model PV-1-1/2. Report FA-1113. Lockheed Aircraft Corporation, Burbank, Calif. March 1944.

13-28 Grimm, O. G., C-47 Nose Vibration Test Procedure. Research Memo. T-1338A. Douglas Aircraft Company, Santa Monica, Calif. January 1944.

13-29 Kerr-Wilson, W., Vibration in Aircraft. Oscillation Sub-Committee of the Aeronautical Research Committee, The de Havilland Aircraft Company, Ltd., Hatfield, Herts, England. 1943.

13-30 Reiher, H., and Meister, F. J., "Die Empfindlichkeit des Menschen gegen Erschütterungen." (Human Sensitivity to Vibration). Forsch. Gebiete Ingenieurw., Vol. 2(11). 1931. pp. 381-386.

EFFECTS OF VIBRATION ON VISUAL PERFORMANCE (Cont)

13-31 Sonneborn, H. M., Noise and Vibration Reduction - Models PV-1 and [illegible]. Report FA-1115. Lockheed Aircraft Corp., Burbank, Calif. March 1944.

13-32 Wulfeck, J. W., The Minimum Amplitude of Vibration Visually Perceptible as Related to Frequency of Vibration and Other Variables. Dept. of Psychology, Tufts College. 1948.

13-33 Zand, S. J., "A Study of Airplane and Instrument-Board Vibration." Journal S.A.E. Vol. 29, 1932. pp. 263-270, 315.

ARRANGEMENT OF INSTRUMENTS

13-34 Baker, C. A., and Grether, W. F., Visual Presentation of Information. WADC Tech. Report 54-160. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. August 1954.

13-35 Cole, E. L., Milton, J. L., and McIntosh, B. B., Routine Maneuvers under Day and Night Conditions, Using an Experimental Panel Arrangement: The Ninth of a Series of Reports on Eye Fixations of Aircraft Pilots. WADC Tech. Report [illegible] Wright-Patterson Air Force Base, Ohio. [illegible]

13-36 Corbelli, D. E., and Lythgoe, R. J., "Some Experiments on Eye Movements." Brit. J. Ophthal. Vol. 13. No. 29. pp 433

13-37 Fitts, P. M., Jones, R. E., and Milton, J. L., Eye Fixations of Aircraft Pilots. III. Frequency, Duration and Sequence Fixations when Flying Air Force Ground-Controlled Approach System (GCA). Tech. Report 5967. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. February 1950.

13-38 Fitts, P. M., and Simon, C. W., The Arrangement of Instruments, the Distance between Instruments and the Position of Instrument Pointers as Determinants of Performance in an Eye-Hand Coordination Task. Tech. Report No. 5832. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. February 1952.

13-39 Jones, R. E., Milton, J. L., and Fitts, P. M., Eye Fixations of Aircraft Pilots. IV. Frequency, Duration and Sequence of Fixations during Routine Instrument Flight. Tech. Report No. 5975. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. March 1950.

13-40 Jones, R. E., Milton, J. L., and Fitts, P. M., Eye Fixations of Aircraft Pilots. I. A Review of Prior Eye-Movement Studies and a Description of a Technique for Recording the Frequency, Duration, and Sequences of Eye Fixations during Instrument Flight. Tech. Report No. 5837. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. September 1949.

13-41 Klass, P. J., "ALPA Urges New Instrument Panel." Aviation Week. Vol. 65. No. 11. September 10, 1956. pp. 50-55.

13-42 McFarland, R. A., Human Factors in Air Transport Design. McGraw-Hill Book Co., Inc., New York, N. Y. 1946.

13-43 McGehee, W., Unpublished Data reported in Reference (13-40) above.

13-44 McGehee, W., Comparative Study of Pilot Fatigue Resulting from Extended Instrument Flight Using the Standard AAF and British Instrument Panels. Final Report. Project TED. No. ATL-R 601, U.S.N.

ARRANGEMENT OF INSTRUMENTS (Cont)

13-45 Milton, J. L., Jones, R. E., and Fitts, P. M., Eye Fixations of Aircraft Pilots. II. Frequency, Duration and Sequence of Fixations When Flying the USAF Instrument Low Approach System. (ILAS). Tech. Report No. 5839. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. October 1949.

13-46 Milton, J. L., Jones, R. E., and Fitts, P. M., Eye Fixations of Aircraft Pilots. V. Frequency, Duration and Sequence of Fixations When Flying Selected Maneuvers during Instrument and Visual Flight Conditions. Tech. Report No. 6018. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. August 1950.

13-47 White, W. J., The Effect of Dial Diameter on Ocular Movements and Speed and Accuracy of Check Reading Groups of Simulated Engine Instruments. Tech. Report No. 5826. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. June 1949.

COCKPIT ILLUMINATION

13-48 Anon. Committee on Standards of Quality and Quantity for Interior Illumination. Illum. Engng. Soc. Report No. 1. Vol. 39. 1944. pp. 713-723.

13-49 Anon. Dark Adaptation Following Exposure of the Eyes to Light of Different Colours, Including Red, Orange, Green and Blue. Admiralty Res. Lab., Teddington, England. ARL/N.9/0.260. February 1943.

13-50 Anon. Evaluation of Proposals for Improved Visibility Inside Aircraft Cockpits. U. S. Naval Air Test Center, U. S. Naval Air Station, Patuxent River, Md. Project TED No. PTR AC-1226. Final Report. March 1953.

13-51 Alsher, D., and Laso, J., A Study of the Requirements for Background Lighting of Aircraft Instruments and Lucite Illuminated Consoles. Part 3. Investigations in the Floodlighting of Transilluminated Cockpit Displays. U. S. Naval Air Experimental Station, Philadelphia, Pa. Aeronautical Medical Equipment Laboratory. Report TED NAM El-606. Part 3. October 17, 1951.

13-52 Brown, F. R., Survey of Lighting Preferences of a Group of Naval Aviators in the XAM-2 Cockpit Mock-up. Report TED No. NAMEL-600. Part 1. U. S. Naval Air Experimental Station, Philadelphia, Pa. October 1948.

13-53 Brown, K. T., and Grether, W. F., The Effects of Pure Red and Low-Color Temperature White Instrument Lighting upon Dark-Adapted Visual Thresholds. USAF Tech. Report No. 6470. Wright Air Development Center, Aero. Med. Lab. RDO No. 694-41. April 1952.

13-54 Chapanis, A., "How We See. A Summary of Basic Principles." Chapter 1 in Human Factors in Undersea Warfare. National Research Council, Washington, D. C. 1949.

13-55 Cote, E. L., McIntosh, B. B., and Grether, W. F., Brightness Levels of Three Instrument Lighting Systems Used by Pilots Flying at Night. Tech. Report No. 6031. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. August 1950.

13-56 Commery, E. W., Studies of Illumination and Brightness in Residential Interiors. Illum. Engng. Soc. Vol. 42. 1947. pp. 87-107.

13-57 Craik, K. J. W., Instrument Lighting for Night Use. Great Britain. FPRC Report No. 342. July 1941.

COCKPIT ILLUMINATION (Cont)

13-58 Crook, M. N., Hanson, J. A., and Wulfeck, J. W., The Legibility of Type as a Function of Reflectance of Background under Low Illumination. WADC Tech. Report 51-85. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. June 1952.

13-59 Ferguson, H. H., and McKellar, T. P. H., "The Influence of Chromatic Light Stimulation on the Subsequent Rate of Perception under Conditions of Low Illumination." Brit. J. Psychol. Vol. 34. 1943-1944. pp. 81-88.

13-60 Ferree, C. E., and Rand, G., "Visibility of Objects as Affected by Color and Composition of Light. Part II. With Lights Equalized in Both Brightness and Saturation," Personnel J. Vol. 10. 1931. pp. 108-124.

13-61 Ferree, C. E., and Rand, G., "Visibility of Objects as Affected by Color and Composition of Light. Part II. With Lights of Equal Luminosity or Brightness." Personnel J. Vol. 9. 1931. pp. 475-492.

13-62 Fry, G. A., and Alpern, M., Armed Forces -- National Research Council Vision Committee. 1953.

13-63 Fry, G. A., and Enrig, N., Effect of Flashes of Light Through the Closed Eyelid. Part 1. Preservation of Dark Adaptation during a Flash by Closing the Eyelids. WADC Tech Report 53-159. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. 1953.

13-64 Fry, G. A., and Enrig, N., Effect of Flashes of Light through the Closed Eyelid. Part 2. Use of Dark Grease on the Closed Eyelids as a Means of Preserving Dark Adaptation during a Flash of Light. WADC Tech. Report 53-159. Wright Air Development Center. Wright-Patterson Air Force Base, Ohio. 1953.

13-65 Hecht, S., and Hsia, Y., "Dark Adaptation Following Light Adaptation to Red and White Lights." J. Opt. Soc. Amer. Vol. 35. 1945. pp. 261-267.

13-66 Hulburt, E. O., "Time of Dark Adaptation after Stimulation by Various Brightnesses and Colors." J. Opt. Soc. Amer. Vol. 41. 1951. pp. 402-404.

13-67 Lacey, R. J., Suitability of the Gray Instrument Panel for Use in USAF Aircraft. Tech. Note WCRD 54-12. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. April 1954.

13-68 Lazo, J., Human Engineering Investigation of Interior Lighting of Naval Aircraft. Part 1. Coloring for Single Seat Aircraft Cockpits. Naval Air Experimental Station, Aeronautical Medical Equipment Lab. TED No. NAMEL-52004. April 1954.

13-69 Luckiesh, M., and Taylor, A. H., "A Summary of Researches in Seeing at Low Brightness Levels." Illum. Engng. Vol. 38. 1943. pp. 189-207.

13-70 Mandelbaum, J., and Rowland, L. S., Central and Paracentral Acuity at Different Levels of Illumination. Army Air Force School of Aviation Medicine. Research Report No. 1. Project No. 230. June 23, 1944.

13-71 Miles, W. R., "Effectiveness of Red Light on Dark Adaptation," J. Opt. Soc. Amer. Vol. 43. 1953. p. 541.

13-72 Pochin, E. E., and Wright, H. B., Coloured Light in Map Reading. Great Britain. Medical Research Council. BPC 44/362. July 1944.

COCKPIT ILLUMINATION (Cont)

13-73 Rock, M. L., "Visual Performance at Low Photopic Brightness Levels." J. Appl. Psychol. Vol. 37. 1953. pp. 413-427.

13-74 Rowland, W. M., and Sloan, L. L., "Relative Merits of Red and White Light of Low Intensity of Adapting the Eyes to Darkness." J. Opt. Soc. Amer. Vol. 34. 1944. pp. 601-604.

13-75 Spragg, S. D. S., and Kanwisher, J., The Effects of Brightness and Color of Illumination on Performance of a Complex Perceptual Motor Task. (Flying a Link Trainer). WADC Tech. Report 52-303. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. July 1952.

13-76 Spragg, S. D. S., and Rock, M. L., "Dial Reading Performance as a Function of Brightness." J. Appl. Psychol. Vol. 36. 1952. pp. 128-137.

13-77 Spragg, S. D. S., and Rock, M. L., "Dial Reading Performance as a Function of Color of Illumination." J. Appl. Psychol. Vol. 36. June 1952. pp. 196-200.

13-78 Stevens, S. S., Handbook of Experimental Psychology. John Wiley and Sons, New York, N. Y. 1951.

13-79 Wilcox, Lawrence R., and Cole, Edward L., The Effects of Two Instrument Lighting Systems on Dark Adaptation. WADC Tech. Report 52-303, Aero Medical Lab., RDO No. 694-41. December 1952.

13-80 Wulfeck, J. W., Review of the Literature on Aeronautical Chart Development and Design for Use under Red Lighting. WADC Tech. Report 52-306. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. July 1952.

GENERAL BIBLIOGRAPHY

13-81 Anon. Built-In Lighting and Planned Environments (Trans. Lighted Ceilings, Recessed Lighting Units, Luminous Environment, Sound and Heat Control). Application Engineering Dept., General Electric Co., Lamp Div. December 1954.

13-82 Anon. Ease of Reading and Visual Acuity in Red and White Light. Great Britain. ARL, Teddington, England. ARL/N.3/0.360. August 1942.

13-83 Anon. Effect of Night Vision on R.A.F. Fluorescent Lighting System and Standard Luminous Paint System. Great Britain. Royal Air Force, Physiological Lab., Farnborough, England. Report 38/12, R.A.F.P.L., OSRD No. WA-3127-5a. December 10, 1941.

13-84 Anon. "The Interreflection Method of Predetermining Brightnesses and Brightness-Ratios." Illum. Engng. Vol. 41. No. 5. May 1956. pp. 361-385.

13-85 Anon. Layout of Cockpits with Particular Reference to Night Visibility and Lighting. Great Britain. Royal Aircraft Establishment, Electrical Engineering Dept., Farnborough, England. Memo 727, EL/G. 2226/D/ESC/33. OSRD No. W-165-14. February 1942.

13-86 Anon. Pilot Performance with Two Different Attitude Displays. Office of Naval Research, Bureau of Aeronautics, Dunlap and Associates, Inc. Contract Nonr 1076(00). July 1955.

13-87 Anon. "Recommended Practice for Supplementary Lighting." Illum. Engng. November 1952.

13-88 Anon. Selective Spectrum Lighting for CIC Areas. U. S. Navy Electronics Lab., San Diego, Calif. Report 337. November 1952.

13-89 Anon. Study on Radium Luminous Material. U. S. Army Service Forces, Office of Chief Ordnance Officer. February 1945.

13-90 Anon. A Study of the Requirements for Letters, Numbers and Markings to be Used on Trans-Illuminated Aircraft Control Panels. Part 3. The Effect of Stroke-Width and Form upon the Legibility of Numerals. Naval Air Experimental Station, Aeronautical Medical Equipment Lab., Philadelphia, Pa. Report TED NAM EL-609. May 1951.

13-91 Anon. "Visibility Levels." Illum. Engng. Vol. 41. No. 5. May 1946. pp. 351-360. Illum. Engng. Vol. 42. February 1947. p. 234.

13-92 Andreas, B. G., Bibliography of Perceptual-Motor Performance under Varied Display-Control Relationships. USAF Human Factors Office of the Rome Air Development Center, Scientific Report 1. 1953.

13-93 Andreas, B. G., and Weiss, Bernard, Review of Research on Perceptual-Motor Performance under Varied Display-Control Relationships. USAF Human Factors Office of the Rome Air Development Center. Scientific Report 2. 1954.

13-94 Armstrong, Harry G., Aircraft Instrument Lighting. U. S. Army Air Forces, Materiel Div., Experimental Engineering Sect. January 8, 1940

13-95 Armstrong, R. C., Aeronautical Charts Prepared for Use in Daylight, under White, Ultra-Violet, Red and Amber Lights. U. S. Army Air Force, Materiel Command, Engineering Div., Aero Medical Lab. Ser. No. ENG-49-698-1. October 6 1943

13-96 Atkinson, William H., Crumley, Lloyd M., and Willis, M. P., A Study of the Requirements for Letters, Numbers, and Markings to be Used on Trans-Illuminated Aircraft Control Panels. Part 5. The Comparative Legibility of Three Fonts for Numerals. U. S. Naval Air Experimental Station, Philadelphia, Pa. Aeronautical Medical Equipment Lab., Naval Air Materiel Center. Report TED NAM EL-609. Part 5. June 13, 1952.

13-97 Barber, J. L., and Garner, W. R., "The Effect of Scale Numbering on Scale-Reading Accuracy and Speed." J. Exp. Psychol. Vol. 41. No. 4. April 1951. pp. 298-309.

13-98 Barr, A. C., Clark, O. N., and Hessler, Joan. Evaluation of Color Rendition by Fluorescent Lamps -- An Exploratory Study. 1952.

13-99 Bartlett, N. R., Reed, J. D., and Duvoisin, G., "Estimations of Distance on Polar Coordinate Plots as a Function of the Scale Used." J. Gen. Psychol. Vol. 41. 1949. pp. 47-65.

13-100 Beebe-Center, J. G., Hoffman, A. C., Mead, L. C., Wagoner, K. S., and Waterhouse, B. R., Training Div., Laboratory of Sensory Psychology and Physiology, Tufts College. August 30, 1944.

13-101 Bell, John M., A Landing Display for Use with a Contact Flight Simulator. Special Devices Center Report 71-16-8. University of Illinois, Urbana, Ill. March 1951.

13-102 Berger, Curt, "Legibility of Letters." Nordisk Medicin. Vol. 45. 1951. p. 788 ff. O.N.I. Trans. No. 1186. July 13, 1953.

13-103 Berger, C., "The Influence of Strokewidth upon the Legibility (Threshold of Recognition) of Some Narrow Numerals of Varying Height." Acta Ophthalmol. Vol. 30. 1952. pp. 409-420.

13-104 Berger, C., "Some Experiments on the Width of Symbols as Determinants of Legibility." Acta Ophthalmol. Vol. 26. 1948. pp. 517-550.

13-105 Berry, Richard N., Brown, Robert H., Mead, Leonard C., Nale, J. R., Searle, Lloyd V., and Wagoner, K. S., Errors in Reading Scales and Changing Deflections of Panoramic Telescopes. U. S. Office of Scientific Research and Development., National Defense Research Committee. OSRD No. 5070. Tufts College. Project SOS-11. Report No. 4. May 18, 1945.

13-106 Bitterman, M. E., "Lighting and Visual Efficiency: The Present Status of Research." Illum. Engng. Vol. 43. 1948. pp. 906-922.

13-107 Blackwell, H. Richard, "Use of Performance Data to Specify Quantity and Quality of Interior Illumination." Illum. Engng. Vol. 50. No. 6. June 1955. pp. 286-[illegible]

13-108 Blackwell, H. Richard, "The Problem of Specifying the Quantity and Quality of Illumination." Illum. Engng. Vol. 49. No. 2. February 1954. pp. 93-97.

13-109 Blackwell, H. Richard, "Brightness Discrimination Data for the Specification of Quantity of Illumination." Illum. Engng. Vol. 47: November 1952.

13-110 Boardman, L. J., The Use of Radioactive Self-Luminous Markers as Sources of Illumination. U. S. Naval Research Lab., Washington, D. C. Report No. 4560. July 18, 1955.

13-111 Boardman, L. J., and Dawson, [illegible], Visibility of Characters at Low Levels of Illumination. U. S. Naval Research Lab., Washington, D. C. 1950.

13-112 Boynton, Robert M., Bush, William R., and Enoch, J. M., "Rapid Changes in Foveal Sensitivity Resulting from Direct and Indirect Adapting Stimuli." J. Opt. Soc. Amer. Vol. 44. January 1954. pp. 56-60.

13-113 Bradley, J. V., and Stump, N. E., Minimum Allowable Knob Crowding. WADC Tech. Report 55-455. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. December 1955.

13-114 Bridgman, C. S., "An Analysis of Taylor's Data on Relative Luminous Efficiency of Various Colors." J. Opt. Soc. Amer. Vol. 44. 1954. pp. [illegible].

13-115 Brindley, G. S., "The Colour of Light of Very Long Wavelength." J. Physiol. Vol. 130. No. 1. 1955. pp. 35-44.

13-116 Broadbent, D. E., Successive Responses to Simultaneous Stimuli. Great Britain. Medical Research Council. FPRC, Applied Psychology Research Unit, Cambridge, England. FPRC 934, RNP 55/837. April 1955.

13-117 Broadbent, D. E., The Twenty Dials Test under Quiet Conditions. Great Britain. Medical Research Council, Applied Psychology Research Unit. A.P.U. 130/50. Psychological Lab., Cambridge, England. August 1950.

13-118 Bromer, John A., Army-Navy-OSRD Vision Committee. Minutes and Proceedings of the Eighth Meeting. December 13, 1944. pp. 24-44. (CONFIDENTIAL)

13-119 Brown, Fred R., A Study of the Requirements for Letters, Numbers and Markings to be Used on Trans-Illuminated Aircraft Control Panels. Part 4. Legibility of Uniform Stroke Capital Letters as Determined by Size and Height to Width Ratio and as Compared to Garamond Bold. Report TED NAM EL-609 Part 4. U. S. Naval Air Experimental Station, Philadelphia, Pa. March 10, 1953.

13-120 Brown, Fred. R., A Study of Requirements for Color, Size, and Shapes of Aircraft Instrument Dial Markings. Part I. Type and Format for Sight Reduction Tables. Report TED NAM EL-618. Part I. U. S. Naval Air Experimental Station, Philadelphia, Pa. December 20, 1949.

13-121 Brown, Fred R., A Study of the Applicability of Indirect Illumination Methods to Individual Aircraft Instruments. Report TED NAM EL-318. U. S. Naval Air Experimental Station, Philadelphia, Pa. May 4, 1949.

13-122 Brown, Fred R., A Study of the Legibility of Trans-Illuminated Markings in Aircraft Cockpits. Report TED NAM EL-600. Part 2. U. S. Naval Air Experimental Station, Philadelphia, Pa. February 25, 1949.

13-123 Brown, Fred R., and Lowery, Edward A., A Study of the Requirements for Letters, Numbers and Markings to be Used on Trans-Illuminated Aircraft Control Panels. Part 2. A Survey of Pilot Preferences for Markings for Rheostat Controls. Report TED NAM EL-609. Part 2. U. S. Naval Air Experimental Station, Philadelphia, Pa. February 1, 1950.

13-124 Brown, Fred R., and Lowery, E. A., A Study of the Requirements for Letters, Numbers, and Markings to be Used on Trans-Illuminated Aircraft Control Panels. Part I. The Effect of Stroke Width upon the Legibility of Capital Letters. Report TED NAM EL-609. Part 1. U. S. Naval Air Experimental Station, Philadelphia, Pa. September 26, 1949.

13-125 Brown, Fred R., Lowery, Edward A., and Willis, Marion P., A Study of the Requirements for Letters, Numbers and Markings to be Used on Trans-Illuminated Aircraft Control Panels. Part 3. The Effect of Stroke-Width and Form upon the Legibility of Numerals. Report TED NAM EL-609. Part 3. U. S. Naval Air Experimental Station, Philadelphia, Pa. May 24, 1951.

13-126 Brown, Fred R., and Poppen, John R., "Visual Problems in Designing Improved Indirect Lighting for Aircraft Cockpits." J. Aviat. Med. Vol. 21. No. 1. February 1950. pp. 3-13A.

13-127 Brozek, Josef, and Simonson, Ernst, "Visual Performance and Fatigue under Conditions of Varied Illumination." Amer. J. Ophthal. Vol. 35. 1952. pp. 33-46.

13-128 Bruell, J. H., and Albee, G. W., "Notes toward a Motor Theory of Visual Egocentric Localization." Psychol. Rev. Vol. 62. 1955. pp. 391-400.

13-129 Burnham, R. W., Evans, R. M., and Newhall, S. M.,"Influence on Color Perception of Adaptation to Illumination." J. Opt. Soc. Amer. Vol. 42. 1952. pp. 597-605.

13-130 Calvert, E. S., Russell, J. L., and Sparks, J. W., Comparison of Ultra-Violet Radiation and Red Light as Methods of Illuminating the Instrument Panel on Aircraft. Great Britain. Report EL 1293. OSRD No. WA-1343-2g. Royal Aircraft Establishment, Electrical Engineering Dept., Farnborough, England. July 1942.

13-131 Carr, W. J., and Garner, W. R., "The Maximum Precision of Reading Fine Scales." J. Psychol. Vol. 34. 1952. pp. 85-94.

13-132 Carson, L. D., Miles, W. R., and Stevens, S. S., "Vision, Hearing and Aeronautical Design." Fed. Proc. Vol. 2. No. 2. 1943. pp. 126-129.

13-133 Chalmers, Laurence, Goldstein, Mymon, and Kappauf, William E., The Effect of Illumination on Dial Reading. U. S. Air Force Tech. Report No. 6021. Air Materiel Command E. O. No. 694-15. August 1950.

13-134 Channell, Ralph C., and Tolcott, Martin A., Arrangement of Equipment. 1949.

13-135 Chapanis, A., "Psychology and the Instrument Panel." Sci. Amer. Vol. 188. 1953. pp. 74-82.

13-136 Chapanis, A., Luminescent Materials. U. S. Army Air Forces, Materiel Center, Experimental Engineering Sect. November 4, 1942.

13-137 Chapanis, A., and Leyzorek, M., "Accuracy of Visual Interpolation between Scale Markers as a Function of the Number Assigned to the Scale Interval." J. Exp. Psychol. Vol. 40 1950. pp. 655-667.

13-138 Christensen, Julien M., The Importance of Certain Dial Design Variables in Quantitative Instrument Reading. Tech. Report 55-376. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. 1955.

13-139 Christensen, J. M., The Effect of the Staircase Scale on Dial Reading Accuracy. MCREXD-694-1-P. Aero Medical Lab., Headquarters, Air Materiel Command, Engineering Div., Wright-Patterson Air Force Base, Ohio. October 1948.

13-140 Cohen, Jerome, Binocular Disparity as a Coding Dimension for Pictorial Instrument and Radar Displays. Tech. Report 55-393. Aero Medical Lab., Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. 1955.

13-141 Cohen, Jerome, and Senders, Virginia L., An Experiment in Dial Coding. WADC Tech. Report No. 52-209. Aero Medical Lab., Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. 1953.

13-142 Cohen, J., Vanderplas, J. M., and White, W. J., "Effect of Viewing Angle and Parallax upon Accuracy of Reading Quantitative Scales." J. Appl. Psychol. Vol. [illegible] [illegible] pp. 452-458.

13-143 Conrad, R., The Effects of Very Fast Speeds on Multiple Dial Watching. Great Britain. Medical Research Council, Applied Psychology Research Unit, A. P. U. 115; Psychological Lab., Cambridge, England. October 1949.

13-144 Coonan, T. J., and Klemmer, E. T., Interpolation and Reference Marks in Reading a Linear Scale at Brief Exposures. U. S. Air Force, Air Research and Development Command, Air Force Cambridge Research Center, Operational Applications Lab., Bolling Air Force Base, Washington, D. C. March 1955.

13-145 Craik, K. J. W., Legibility of Different Coloured Instrument Markings and Illuminated Signs at Low Illuminations. Great Britain. CURD Liaison Office Ref. No. WAM-[illegible]-14. Flying Personnel Research Committee Report No. 415. January 15, 1942.

13-146 Crook, M. N., Studies in the Legibility of Numerals. Armed Forces Vision Committee Meeting. February 1950.

13-147 Crook, M. N., Hoffman, A. C., Wessell, N. Y., Wulfeck, J. W., and Kennedy, J. L. Effect of Vibration on Legibility of Tabular Numerical Material. Experiments 1 to 4. M.R. TSEAA-694-1F. U. S. Army Air Force, Air Materiel Command, Engineering Div. 1947.

13-148 Crook, M. N., Hoffman, A. C., Wessell, N. Y., Wulfeck, J. W., and Kennedy, J. L. Effect of Vibration on Legibility of Tabular Numerical Material. Experiments 1 to 4. Unpublished Laboratory Record, Tufts College of Sensory Psychology and Physiology. 1947.

13-149 Crook, M. N., Hoffman, A. C., Wessell, N. Y., Wulfeck, J. W., and Kennedy, J. L., Effect of Vibration on Legibility of Tabular Numerical Material. Experiments 5 to 7. M.R. TSEAA-694-1K. U. S. Army Air Force, Air Materiel Command, Engineering Div. 1947.

13-150 Crumley, Lloyd M., A Study of the Requirements for Letters, Numbers and Markings to be Used on Trans-Illuminated Aircraft Control Panels. Part 7. An Evaluation of the Relative Manipulability of Simple Toggle Switches, Cutler-Hammer Lick-Lever Toggle Switches and Toggle-Switch, Switch-Guard Combinations. Report TED NAM EL-609. Part 7. U. S. Naval Air Experimental Station, Philadelphia, Pa. February 16, 1953.

13-151 Crumley, Lloyd M., A Study of the Requirements for Letters, Numbers and Markings to be Used on Transilluminated Aircraft Control Panels. Part 8. A Proposal for the Standardization of Aircraft Electrical and Electronic Control Knobs. Report TED NAM EL-609. Part 8. U. S. Naval Air Experimental Station, Philadelphia, Pa. December 29, 1948.

13-152 Crumley, Lloyd M., and Willis, Marion P., A Study of the Requirements for Letters, Numbers and Markings to be Used on Transilluminated Aircraft Control Panels. Part 6. A Survey of Pilot Preferences for Special Attention Plate Markings. Report TED NAM EL-609. Part 6. U. S. Naval Air Experimental Station, Philadelphia, Pa. September 18, 1951.

13-153 Dale, H. C. A., The Effect on Performance of Variations in Certain Spatial and Temporal Properties of a Multi-Dial Display. Great Britain. A.P.U. 212/54. Medical Research Council, Applied Psychology Research Unit, Cambridge, England. 1954.

13-154 Devoe, D. B., The Use of Direct Reading Counters in Visual Displays. Spec. Report, Vol. II, No. 1. Tufts College, Institute for Applied Experimental Psychology, Medford 55, Mass. December 1954.

13-155 Dixon, J. C., "Effect of Exposure-Time on Perception of Grouped Digits." Amer. J. Psychol. Vol. 61. 1948. pp. 390-330.

13-156 Dunlap and Associates, Inc., Prepared for Douglas Aircraft Company, El Segundo, Calif December 10, 1954. (CONFIDENTIAL)

13-157 Dunlap, J. W., and Channell, R. C., Analysis of Pilot's Performance in Multi-Engine Aircraft, (R&D). Office of Naval Research, Special Devices Center, Psychological Corp., Div. of Bio-Mechanics. BuMed Project X-651. April 1947.

13-158 Eckenrode, R. T., and Hedberg, R. D., Controls and Displays I: The Detectability of Errors in Certain Geometrical Configurations, Project No. TB1-2000- and TB1-15-C11, Memo Report No. MR-580, Human Engineering Report No. 2. Pitman-Dunn Labs., Frankford Arsenal, Philadelphia, Pa. January 1954.

13-159 Fry, Glenn A., "Effects of Uniform and Non-Uniform Surrounds on Foveal Vision." Amer. J. Optom. and Arch. Amer. Acad. Optom., Monograph No. 105. September 1950.

13-160 Gardner, John F., Direction of Pointer Motion in Relation to Movement of Flight Controls, Cross-Pointer Type Instrument. Tech. Report No. 6016. U. S. Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. June 1950.

13-161 Gardner, John F., and Lacey, Robert J., An Experimental Comparison of Five Different Attitude Indicators. Aero Medical Laboratory Tech. Report 54-32. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. June 1954.

13-162 Garner, W. R., and Gebhard, J. W., Machine Dials and Scales. Machine Design: Penton Publication: 2-9. 1949.

13-163 Gleason, J. G., The Design of Numerals for Use in Counter-Type Instruments: A Review of the Literature. Tech. Report No. SDC 166-1-39. Special Devices Center, Office of Naval Research, Port Washington, L. I., N. Y. December 1947.

13-164 Grether, W. F., Speed and Accuracy of Dial Reading as a Function of Dial Diameter and Spacing of Scale Divisions. TSEAA-694-1. Air Materiel Command, Wright Field, Dayton, Ohio. March 1947.

13-165 Grether, W. F., Kennedy, J. L., Mead, L. C., Seitz, C. P., Gebhard, J. W., Fitts, P. M., and Williams, A. C., Jr., Standards to be Employed in Research on Visual Displays. Armed Forces-National Research Council Vision Committee. 1947. (revised 1950)

13-166 Grether, W. F., and Williams, A. C., Jr., "Psychological Factors in Instrument Readings. II. The Accuracy of Pointer Position Interpolation as a Function of the Distance between Scale Marks and Illumination." J. Appl. Psychol. Vol. 33. 1949. pp. 594-604.

13-167 Hake, H. W., and Garner, W. R., "The Effect of Presenting Various Numbers of Discrete Steps on Scale Reading Accuracy." J. Exp. Psychol. Vol. 42. 1951. pp. 358-366.

13-168 Hale, D. H., Cockpit Lighting. Douglas Aircraft Co., Inc., Santa Monica, Calif., Research Labs. September 5, 1944.

13-169 Harper, W. E., Robinson, Margaret B., and Dowtell, J. N., "The Photometric Properties of Luminescent Materials." Trans. Illum. Engng. Soc. London, England. Vol. 5, No. 5. June 1940. pp. 57-72.

13-170 Hartline, H. K., Army-Navy-OSRD Vision Committee. Minutes and Proceedings of the Eighth Meeting. [illegible] (CONFIDENTIAL)

13-171 Hartline, H. K., Relative Merits of Lights of Different Wave-Lengths in Aircraft Cockpit Illumination. U. S. National Research Council, Committee on Aviation Medicine. Report No. 10. June 1941.

13-172 Hecht, S., Haig, C., and Wald, G., "The Dark Adaptation of Retinal Fields of Different Size and Location." J. Gen. Physiol. Vol. 19. 1935. pp. 321-339.

13-173 Hulburt, E. O., Dark Adaptation Time to Become Dark Adapted after Stimulation by Various Brightness of Colors. Report No. H-2035. U. S. Naval Research Lab. March 30, 1943.

13-174 Hunt, Darwin, P., The Coding of Aircraft Controls. Aero Medical Lab. Tech. Report 53-221. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. 1953.

13-175 Hunt, R. W. G., "The Perception of Color in 1° Fields for Different States of Adaptation." J. Opt. Soc. Amer. Vol. 43. 1953. pp. 479-484.

13-176 Hunt, R. W. G., "Light and Dark Adaptation and the Perception of Color," J. Opt. Soc. Amer. Vol. 42. 1952. pp. 190-199.

13-177 Hurvich, Leo M., and Jameson, Dorothea, "A Psychophysical Study of White. III. Adaptation as Variant." J. Opt. Soc. Amer. Vol. 41. November 1951. pp. 787-801.

13-178 Hyman, R., and Hake, H. W., Form Recognition as a Function of the Number of Forms which Can be Presented for Recognition. WADC Tech. Report 54-164. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. May 1954.

13-179 Imus, Henry A., Dials and Indicators. Tech. Report ONRL-36-52. Office of Naval Research, London, England. 1952.

13-180 Jameson, Dorothea, and Hurvich, Leo M., "Levels of Adaptation and Brightness Changes during Color Adaptation." Science. Vol. 110. No. 2847. July 23, 1949. pp. 92-93.

13-181 Johnsgard, K. W., "Check-Reading as a Function of Pointer Symmetry and Uniform Alignment." J. Appl. Psychol. Vol. 37. 1953. pp. 407-411.

13-182 Johnson, B. E., and Williams, A. C., Obedience to Rotation-Indicating Visual Displays as a Function of Confidence in the Displays. Project 20-L-1. Project Designation NR-784-003. Tech. Report SDC 71-16-2. Office of Naval Research, Special Devices Center, June 1949.

13-183 Kappauf, William E., Design of Instrument Dials for Maximum Legibility. Part 5. Origin Location, Scale Break, Number Location, and Contrast Direction. Tech. Report No. 6366. U. S. Air Force, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. May 1951.

13-184 Kappauf, William E., Some Data on the Influence of Attempted Interpolation on the Speed and Errors of Scale Reading. USAF Tech. Report No. 6590. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. May 1951.

13-185 Kappauf, William E., A Discussion of Scale-Reading Habits. USAF Tech. Report No. 6600. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. July 1951.

13-186 Kappauf, W. E., and Smith, W. M., "A Preliminary Experiment on the Effect of Dial Graduation and Dial Size on the Speed and Accuracy of Dial Reading." Annals N. Y. Aca. Sci. Vol. 51. 1951. pp. 1272-1277.

13-187 Kappauf, William M., and Smith, William A., Design of Instrument Dials for Maximum Legibility. Part 3. Some Data on the Difficulty of Quantitative Reading in Different Parts of a Dial. Tech. Report No. 5914. Part 3. U. S. Air Force, Air Materiel Command, Princeton University. May 1950.

13-188 Kappauf, William E., and Smith, William M., Design of Instrument Dials for Maximum Legibility. Part 4. Dial Graduation, Scale Range and Dial Size as Factors Affecting the Speed and Accuracy of Scale Reading. Tech. Report No. 5914. Part 4. U. S. Air Force, Air Materiel Command, Princeton University. February 1950.

13-189 Kappauf, W. E., and Smith, W. M., Design of Instrument Dials for Maximum Legibility. II. A Preliminary Experiment on Dial Size and Graduation. Report 4. Aero Medical Lab., Engineering Div., Air Materiel Command, Wright Field. May 1948.

13-190 Katz, I., Report No. IDa-22-42, NAF Serial No. 17. Project WIDS-66. U. S. Navy, Naval Aircraft Factory, Philadelphia, Pa. Instrument Development Sect. August 15, 1942. (CONFIDENTIAL)

13-191 Katz, M. S., Morris, A., and Dimmick, F. L., The Effects of Various Durations of Red Adaptation of the Course of Subsequent Dark Adaptation. MRL 13: No. 7. Report No. 246. Project NM 003041.58.01. U. S. Naval Submarine Base, New London, Conn. April 1954.

13-192 Kell, Francis C., Use of Red Light to Facilitate Dark Adaptation. Project No. 118. Report No. 1. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. February 19, 1943.

13-193 Kell, Francis C., Visual Fields in the Dark Adapted State. Project No. 35. Report No. 1. U. S. Air Force of Aviation Medicine, Randolph Field, Texas. December 7, 1942.

13-194 Kell, Francis C., Project. No. 64. Report No. 1. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. July 1, 1942.

13-195 King, B. G., Morrow, Dorothy J., and Vollmer, E. P., Cockpit Studies - The Boundaries of the Maximum Area for the Operation of Manual Controls. Project X-651. Report 3. Naval Medical Research Institute, National Naval Medical Center, Bethesda, Md. July 1947.

13-196 Krulee, G. K., Podell, J. E., and Ronco, P. G., "Effect of Number of Alternatives and Set on the Visual Discrimination of Numerals." J. Exp. Psychol. Vol. 48. 1954. pp. 75-80.

13-197 Krulee, Gilbert K., and Weiss, Alexander, Studies in the Visual Discrimination of Multiple Unit Displays. Report No. 494-03-23, Project No. NR 145-088. U. S. Navy, Office of Naval Research. (Tufts College). August 1953.

13-198 Kuntz, James E., and Sleight, Robert B., "Legibility of Numerals: The Optimal Ratio of Height to Width of Stroke." Amer. J. Psychol. Vol. 63. October 1950. pp. 567-575.

13-199 Lauder, M. K., Floodlighting of Aircraft Instruments. Report 119. Grimes Manufacturing Co., Urbana, Ohio. June 1952.

13-200 Laso, J., Lighting Requirements for Cockpits and Compartments of Naval Aircraft. Part 2. Investigation of Supplementary Floodlighting for Panels Employing Individual Instrument Lighting Fixtures. Report TED No. NAM EL-619. Part 2. XG-T-178. Naval Air Material Center, Philadelphia, Pa. June 1952.

13-201 Laso, J., and Brown, F. R., Color Size and Shapes of Aircraft Instrument Dial Markings. Part II. Design for the Turn and Bank Indicator Adapted to Red Instrument Lighting [illegible] Naval Air Material Center, Philadelphia, Pa. October 1950.

13-202 Laso, J., and Brown, F. R., Instrument Lighting Investigations of Ultra-Violet Reflections. Part II. Measurements of Ultra-Violet Energy in Aircraft Cockpits Equipped with Fluorescent Instrument Lighting. Report TED NAM 11824. Naval Air Material Center, Philadelphia, Pa. February 1950.

13-203 Levett, C. M., "Errors of Interpolation in Instrument Reading and Setting." J. Appl. Psychol. Vol. 36. 1952. pp. 49-53.

13-204 Leyzorek, M., "Accuracy of Visual Interpolation between Circular Scale Markers as a Function of the Separation between Markers." J. Exp. Psychol. Vol. 39. April 1949. pp. 270-279.

13-205 Lincoln, Robert S., and Averbach, Emanuel, "Spatial Factors in Check Reading of Dial Groups." J. Appl. Psychol. Vol. 40. 1956. pp. 105-108.

13-206 Livingston, P. C., The Use of Red Light for Illuminating the Cockpits of Aircraft. Great Britain. OSRD Liaison Office Ref. No. WA-1[illegible]-12. Flying Personnel Research Committee Report No. 268a. February 1941.

13-207 Loeb, M., Bass, W. M., Roberts, E. E., and Samuelsen, M. L., A Further Investigation of the Influence of Whole-Body Vibration and Noise on Tremor and Visual Acuity. Project No. 6-95-20-001. Report No. 165. Dept. of the Army, Army Medical Research Lab., Office of the Surgeon General, Research and Development Div., Fort Knox, Ky. October 1954.

13-208 Logan, H. L., "The Practical Mechanics of Designing Optimum Lighting Patterns." Illum. Engng. Vol. 43. December 1948. pp. 1233-1261.

13-209 Long, G. E., Speed and Accuracy of Readings as a Function of Design in the Sensitive Airspeed Indicator. USAF Tech. Report No. 5830. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. August 1949.

13-210 Long, E. R., and Lee, W. A., The Influence of Specific Stimulus Cuing on Location Responses. WADC Tech. Report 53-314. Wright-Patterson Air Force Base, Ohio. December 1953.

13-211 Long, E. R., and Lee, W. A., The Role of Spatial Cuing as a Response-Limiter for Location Responses, RDO 694-37. Tech. Report 53-312, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. December 1953.

13-212 Long, E. R., and Reid, L. S., Factors Determining the Legibility of Letters and Words Printed in "Dot" Patterns with Differential Brightness of the Patterns Proportional to the Amount of Degradation. The Second of a Series of Reports on the "Informax" Principle. RDO No. 694-37, USAF Tech. Report 5828. Wright Air Development Center, Aero Medical Lab., Wright-Patterson Air Force Base, Ohio. April 1952.

13-213 Luckiesh, Matthew, and Guth, S. K., "Brightness in Visual Field at Borderline between Comfort and Discomfort (BCD)." Illum. Engng. Vol. 44. November 1949. pp. 650-667.

13-214 Meaker, Phelps, and Oetting, R. L., Visual Comfort Index Data and Tables: Their Meaning and Use in Lighting Design. LS-108. General Electric Lamp Div., Application and Engineering Dept. October 1953

13-215 Moon, Parry, and Spencer, Domina Eberle, Lighting Design. 1948.

13-216 [illegible]
BuMed Project NM 003 041,04.03. U. S. Naval Submarine Base, Medical Research Lab., New London, Conn. MRL Report No. 182. Vol. 9. 1950. pp. 157-183.

13-217 [illegible], Army-Navy-OSRD Vision Committee, Minutes of the Eighth Meeting December 12, 1944. p. 45. (CONFIDENTIAL)

13-218 Mote, F. A., Biersdorf, W. R., Kent, G. W., and Myers, Jerome, Visual Contrast Discrimination as a Function of Pre-Exposure to Light. WADC Tech. Report 54-60. Wright Air Development Center. RDO No. 694-40 University of Wisconsin. February 1954.

13-219 Mote, F. A., and Reed, Eleanor C., "The Effect of High Intensity and Short Duration vs. Low Intensity and Long Duration of Intermittent Pre-Exposure upon Human Dark Adaptation." J. Opt. Soc. Amer. Vol. 42. August 1952. pp. 521-525.

13-220 Mote, F. A., and Reed, Eleanor C., "The Effect of Extending the Duration of Various Light-Dark Ratios of Intermittent Pre-Exposure upon Dark Adaptation in the Human Eye." J. Opt. Soc. Amer. Vol. 42. May 1952. pp. 333-338.

13-221 Mote, F. A., and Riopelle, A. J., "The Effect of Varying the Intensity and the Duration of Pre-Exposure upon Subsequent Dark Adaptation in the Human Eye." J. Compar. Physiol. Vol. 46. No. 1. Feburary 1953. pp. 49-55.

13-222 Mote, F. A., and Riopelle, A. J., "The Effect of varying the Light-Dark Ratio of Intermittent Pre-Exposure upon Subsequent Dark Adaptation in the Human Eye." J. Opt. Soc. Amer. Vol. 41. February 1951. pp. 120-124.

13-223 Mote, F. A., and Riopelle, A. J., "The Effect of Varying the Intensity and the Duration of Pre-Exposure upon Foveal Dark Adaptation in the Human Eye." J. Gen. Physiol Vol. 34. May 20, 1951. pp. 657-674.

13-224 Mote, F. A., Riopelle, A. J., and Meyer, D. R., "The Effect of Intermittent Pre-Adapting Light upon Subsequent Dark Adaptation in the Human Eye." J. Opt. Soc. Amer. Vol. 40. September 1950. pp. 584-588.

13-225 Pearsons, R. J., Cory, and Gilbert, M. S., Development of Interior Painting and Lighting for CAA Facilities. Tech. Development Report No. 78. U. S. Dept. of Commerce, Civil Aeronautics Administration. March 1949.

13-226 Petherbridge, P., and Longmore, J., "Solid Angles Applied to Visual Comfort." Light and Lighting. June 1954. pp. 173-177.

13-227 [illegible], Eye-hand span in simple serial Tasks. Great Britain. A.P.U. 184/53. Medical Research Council, Applied Psychology, Cambridge. 1953.

13-228 Reed, J. B., The Speed and Accuracy of Discriminating Differences in Number and Texture-Density. Tech. Report No. SDC-131-1-3. July 1952.

13-229 Reinwald, F. L., Design of Visual Displays. Colgate University, Dept. of Psychology. 1954.

13-230 Ross, S., Ray, W., and Valle, L. D., "Pointer Location and Accuracy of Dial Reading." J. Appl. Psychol. Vol. 37. 1953. pp. 131-135.

13-231 Sandberg, K. O. W., and Lipshultz, N. L., Maximum Limits of Working Areas on Vertical Surfaces. SDC Report 166-1-8. Office of Naval Research. April 1952.

13-232 Schapiro, Harold B., Factors Affecting Legibility of Digits. WADC Tech. Report No 52-127. RDO No. 694-41. University of Rochester. June 1952.

13-233 Senders, Virginia L., The Effect of Number of Dials on Qualitative Reading of a Multiple Dial Panel. WADC Tech. Report No. 52-182. RDO No. 694-51. Antioch College. November 1952.

13-234 Senders, Virginia L., and Cohen, J., The Effects of Absolute and Conditional Probability Distributions of Instrument Settings on a Scale Reading: Repeated Exposures of the Same Setting. WADC Tech. Report 54-[illegible] Wright Air Development Center, Wright-Patterson Air Force Base, Dayton, Ohio October 1954.

13-235 Senders, Virginia L., Cohen, Jerome, and Arginteanu, Mary, The Effects of Absolute and Conditional Probability Distributions on Instrument Reading. II. A Comparison of a Linear and a Logarithmic Scale. WADC Tech. Report No. 54-253. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. 1955.

13-236 Shackel, B., The Human Limbs in Control. 2. Optimum Control-Display Ratios at Different Display Distances. Great Britain. A.P.U. 215/54. Medical Research Council, Applied Psychology Research Unit. April 1954

13-237 Simonson, Ernst, and Brozek, Josef, "Effects of Illumination Level on Visual Performance and Fatigue." J. Opt. Soc. Amer. Vol. 38. 1948. pp. 384-397.

13-238 Simonson, Ernst, and Brozek, Josef, "The Effect of Spectral Quality of Light on Visual Performance and Fatigue." J. Opt. Soc. Amer. Vol. 38. 1948. pp. 830-840.

13-239 Sleight, Robert B., "The Effect of Instrument Dial Shape on Legibility." J. Appl. Psychol. Vol. 32. 1948. pp. 170-188.

13-240 Soar, R. S., "Height-Width Proportion and Stroke Width in Numeral Visibility." J. Appl. Psychol. Vol. 39. 1955. pp. 43-46.

13-241 Spragg, S. D. S., and Rock, M. L., "Dial Reading Performance as a Function of Brightness." J. Appl. Psychol. Vol. 36. April 1952. pp. 128-137.

13-242 Spragg, S. D. S., and Rock, M. L., Dial Reading Performance as Related to Illumination Variables. II. Spectral Distribution. USAF Report MCREXD-694-21A. Wright-Patterson Air Force Base, Ohio. December 1949.

13-243 Spragg, S. D. S., and Rock, M. L., Dial Reading Performance as Related to Illumination Variables. III. Results with Small Dials. USAF E. O. No. 694-41. Tech. Report 6040. Wright-Patterson Air Force Base, Ohio. November 1950.

13-244 Spragg, S. D. S., and Rock, M. L., Dial Reading Performance as Related to Illumination Variables. I. Intensity. USAF Report I. Wright-Patterson Air Force Base, Ohio. October 1948.

13-245 Spragg, S. D. S., and Wulfeck, J. W., "The Effect of Immediately Preceding Task Brightness on Visual Performance." J. Appl. Psychol. Vol. 39. 1955. pp. 237-243.

13-246 Stellar, Eliot, Human Factors in Panel Design. 1949. p. 13.

13-247 Tinker, Miles A., "Effect of Vibration upon Reading." Amer. J. Psychol. Vol. 61. 1948. pp. 376-390.

13-248 Vanderplas, James M., Interior Color Schemes for Aircraft Gray Instrument Panel. WADC Tech. Note ACRD 53-71. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. June 1953.

13-249 Wapner, S., and Werner, H., "Experiments on Sensory-Tonic Field Theory of Perception: V. Effect of Body [illegible] on the Kinesthetic Perception of Verticality." J. Exp. Psychol. Vol. 44. 1952. pp. 126-131.

13-250 White, William J., The Effect of Pointer Design and Pointer Alignment Position on the Speed and Accuracy of Reading Groups of Simulated Engine Instruments. USAF Tech. Report No. 6014. Wright Air Development Center, Wright-Patterson Air Force Base. July 1951

13-251 Zigler, Michael J., Wolf, Ernst, and King, Esther Shores, "The Influence of Surround Brightness and Short Wave Components of Radiation on Dark Adaptation." J. Opt. Soc. Amer. Vol. 41. No. 5. 1951. pp. 354-359.

CHAPTER 14

INSTRUMENT NAVIGATION, APPROACH, AND LANDING

This chapter is in three parts. The first part deals with the task of instrument navigation and considers the displays used in conjunction with this aspect of flight.

The second part examines the difficulties involved in instrument approach and landing. Some of the reasons for the difficulty of this flight operation are discussed in relation to present techniques and instruments. Techniques for bringing about safer and simpler landings are evaluated.

A discussion of maps and charts is included as the third part of this chapter, since in many current aircraft, maps and charts must still be used.

We can best begin by describing in general the different aspects or parts of the task of navigation.

What is it that the aircrewman is doing when he navigates? Typically, navigation involves a series of steps or legs leading to the destination. Within each such leg, the attempt is made, either continously or intermittently, to ascertain the position of the aircraft over the terrain below with minimum uncertainty and error. This is the first aspect of navigation - knowing where the aircraft is.

The second aspect is that of planning the steps necessary for the completion of a course to the next checkpoint or destination. Here the effort is made to predict the heading which, taking account of atmospheric conditions, will get the aircraft to the next checkpoint at a particular time.

The third aspect is concerned with maintaining the required heading and other required flight conditions. This aircraft control or tracking task is continuous as contrasted with the first two aspects, which are typically intermittent tasks concerned with maintaining orientation and decision-making.

Let us consider now the navigational displays used in conjunction with these three aspects of instrument navigation. Until recently, maintaining orientation and decision-making required the use of a map or radio facility chart in conjunction with the panel-mounted navigation displays. This was necessary because radio navigation aids provide only bearing information without continuous information on the distance of the aircraft from the ground facility. The lack of distance information necessitated dead reckoning from an occasional position fix to the next checkpoint or merely homing in on a station without knowledge of distance-to-go and present position.

Two points are of interest here. First, maintaining orientation and decision-making under these conditions require the operator to integrate information appearing on the navigational display and the map or facility chart. This requires mental manipulation or transformation of the information, or manually plotting the navigational display read-out on the map. While this is not a critical consideration where a full-time navigator is aboard, it imposes a heavy load upon the pilot of a single-place high-performance aircraft. Secondly, the navigational displays which have been developed to display bearing information are primarily designed to facilitate the aircraft control or tracking task, rather than the other aspects of navigation. An example of such a display is the Radio Magnetic Indicator, in which two radio compass pointers indicate bearing against a moving scale indication of heading. The display is used for controlling heading, for homing, and for obtaining a fix from bearings to two stations. However, utilizing a two-bearing fix for orientation and decision-making ordinarily requires the use of a map or radio facility chart.

The development of the omni-directional radio range (omni-range) and associated distance measuring equipment, of Tacan, and of airborne automatic dead-reckoning equipments have made it possible to continuously indicate to the pilot the position of his aircraft. These developments raise the question of how to display this information to the pilot so as to allow him to carry out the decision-making and tracking functions of navigation with maximum accuracy and efficiency. A fund of valuable data relating to this question has resulted from a series of experiments conducted at the University of Illinois. 14-15, 14-20 These experiments were undertaken to determine optimum display designs for use with VOR. In an initial experiment, speed and accuracy of pilots' solutions of typical

navigation problems were compared by means of mockups (drawings) of three proposed pictorial displays and five existing symbolic displays. The symbolic displays employed numerical pointer readings, needle deflections, or numbers appearing in windows, while the pictorial displays provided information in the form of representations of the spatial relations between aircraft, station, and aircraft heading. The pictorial displays were found to be superior to the symbolic displays in terms of both time and error scores. A pictorial display of the type shown in Figure 14.1, in which the station is shown in a fixed position at the center of the display with north at the top and the aircraft as a pip moving about the station, was superior to all others. In subsequent tests, performance on this display was compared with that on the conventional symbolic display shown in Figure 14.2. Private pilots and instrument pilots flew a variety of local navigational problems in a Link Trainer. Results of the experiments favor the pictorial display in terms of: (1) the excess distance flown on correct solutions; (2) the distance flown in which established flight tolerances for altitude and airspeed were exceeded; (3) the number of unnecessary turns which were made; (4) the time required to orient from an unknown position and initiate a problem solution; (5) the proportion of first turns which were made in a more economical direction; and (6) the proportion of first turns which resulted in a correct initial heading. The symbolic display showed superiority only in accuracy of hitting the station on a final straight-in approach.

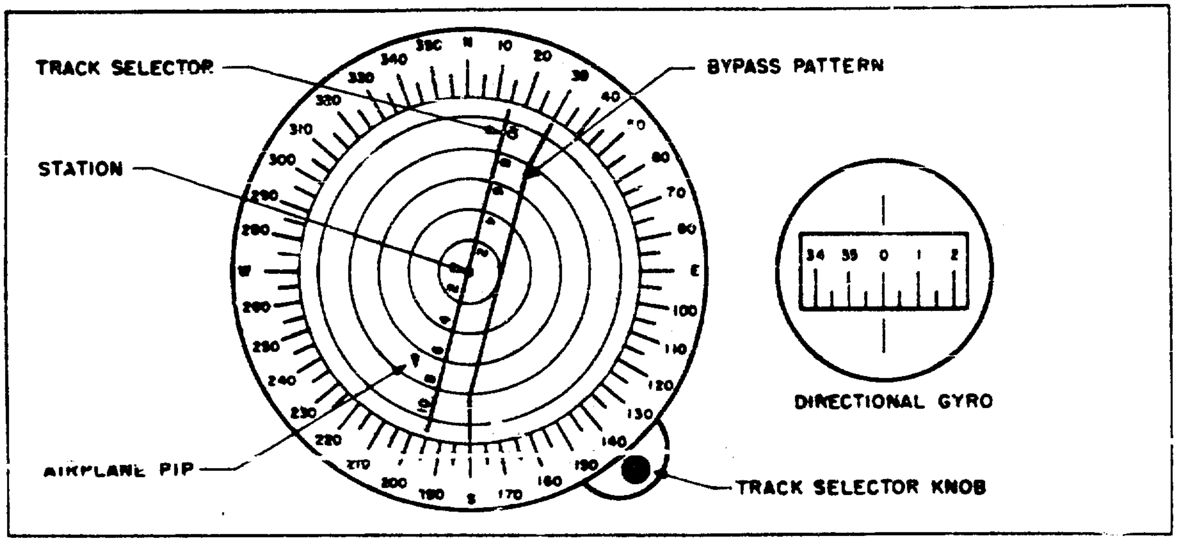


Figure 14.1 The Station-Centered Pictorial Display

The display indicates directly the position and heading of the aircraft in relation to the station.[14-15]

Another experiment [14-14] showed that performance on pictorial displays was superior when the moving figure represented the aircraft rather than the station. Another finding here was that it made no significant difference whether the compass rose was oriented with north at the top or rotated so that north appeared at some other position, although there was a small difference in favor of the 12 o'clock north orientation.

These experiments definitely establish that for the orientation and planning functions involved in navigation a map-like pictorial display in which the aircraft symbol moves relative to a fixed ground representation is optimum. This is an application of the "outside - in" display principle discussed in Chapter 13. The data indicate, however, that such a display is probably not equally good for precise heading control. It is possible, however, to design a composite instrument incorporating information in optimum form for both planning and precise tracking control. One solution would be to allow the entire display, including the fixed compass rose, to be rotated so that the desired course appears at the top of the display. Adding a moving bug which indicates actual heading against the compass rose would then allow the pilot to check-read his steering control against the 12 o'clock reference position.

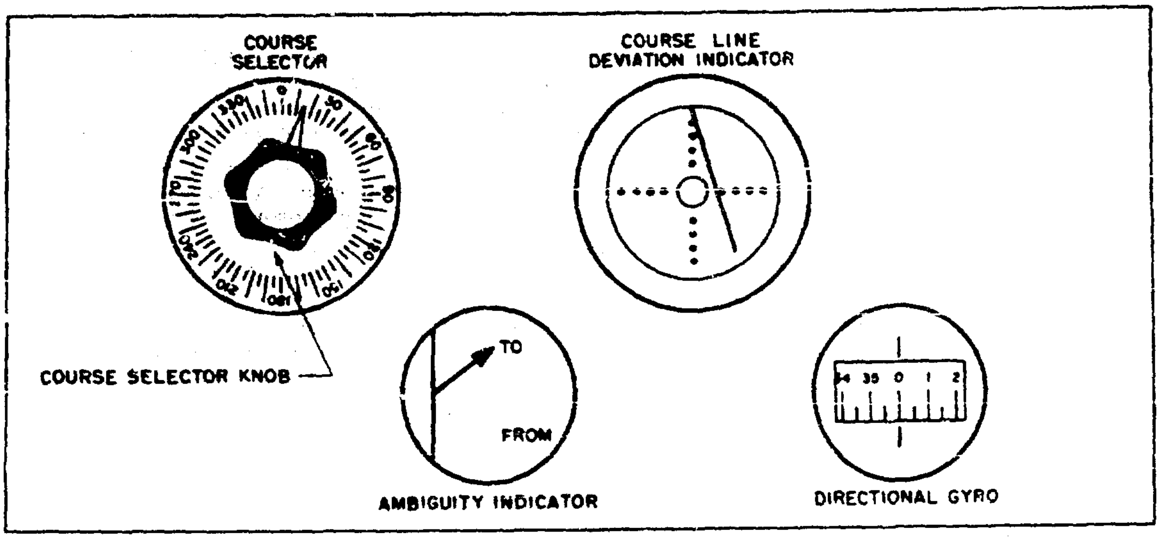


Figure 14.2 The Conventional Symbolic Display

The display indicates that the aircraft is somewhere to the left of a course of 15° to the station, heading N. 14-15

Applications of the pictorial display principles evolved in the studies at the University of Illinois have been made in more recent navigational display development programs. These include several Portable Pictorial Display equipments developed by the Air Navigation Development Board, 14-16, 14-17, 14-18 as well as interceptor navigational displays developed at the Hughes Aircraft Company. These displays indicate aircraft position or track on variable-scale map backgrounds.

An advantage of this type of display for further development is that the specific information appearing on the map or chart background can be varied to suit the requirements of the particular aircraft mission. Moreover, it should be possible to display such additional information as is available from airborne computers and other automatic equipment in the form most readily interpreted by the human operator in planning and decision-making. Such additional information might include fuel range indication, position of other aircraft, command headings, or a representation of the entire predicted course of the mission.

INSTRUMENT APPROACH AND LANDING

One aspect of the pilot's job on an instrument approach is to provide a stable, well-controlled heading and rate of descent. In this regard, the approach task does not differ from other phases of instrument flight. Time pressures are heightened, since these adjustments in flight path must be established quickly and accurately at precisely designated times. On a ground-controlled approach (GCA), this is the major part of the pilot's responsibility; he maintains a stable, precise flight path from which necessary corrections can be established by ground personnel, and then he executes the corrections as directed.

On an instrument low-approach system (ILAS), the pilot's information processing load is increased by the necessity to monitor the cross-pointer instrument in addition to the other instruments on the panel. An idea of the increased load can be inferred from data of the eye movement studies described in Chapter 12. These data show that about 40 percent of the pilot's time is devoted to watching the cross-pointer instrument.

The reduction in the time available during the ILAS approach for scanning other instrument indications appears to be of importance in terms of the following analysis of how the pilot utilizes the cross-pointer information during the approach. Essentially, the cross-pointer instrument supplies the same kind of information supplied by the ground controller on GCA approaches. If the pilot has been able to hold a precise heading and rate of descent, he is more able to predict the control actions which will be required to hold the cross-pointer indices zeroed after he has made a correction. If the pilot merely chases the cross-pointer needles without being able to smooth out the oscillations of flight

path, there is little possibility that he will be able to hold the narrowing beam as he gets nearer the runway.

The pilot's visual information processing load is further increased during an approach when he begins to search outside the aircraft to establish visual reference. At this point the pilot must not only integrate cross-pointer and flight instrument information, but must also curtail and interrupt this activity to try to identify the runway, approach lights, or other ground objects so as to effect the transition to visual flight. Two points are of importance here. First, establishing ground reference at night and under the low visibility conditions often encountered may not be quickly accomplished, requiring appreciable time for searching and interpretation of the few ambiguous visual cues available. Secondly, switching back and forth between instrument flight and visual reference, which often occurs with a low overcast, requires a change between different frames of reference. This results in the same impairment of performance and possibility of confusion in both visual tasks as pointed out earlier in Chapter 13.

One approach to the problem of instrument landing, it would appear, is to consider the various current and experimental landing systems in terms of how they relate to the information processing load of the human operator. Viewed from this standpoint, the low frequency aural range and GCA procedures reduce the visual load upon the pilot. Since steering directions are received aurally, more time is available for visually scanning and interpreting flight instruments.

A study [14-8] demonstrated the gain in performance achieved by dividing the information load between several sensory channels. Three different techniques of presenting airspeed information were compared in a laboratory simulation of carrier landings. Subjects performed a visual alignment task while simultaneously attempting to maintain a constant airspeed indication. Airspeed was more accurately controlled when presented aurally (varying pulse rate and intensity) than when presented by the standard airspeed indicator. Somewhat better than the standard airspeed indicator, but not as good as the aural presentation, was the display of airspeed by projecting lights varying in color, flash rate, and intensity on the windscreen.

Probably the most effective means yet devised for lightening the pilot's load during the approach are the military and civilian automatic approach systems in which the autopilot is utilized to control the aircraft during the approach. With these systems, the operator is largely relieved of the task of maintaining a stable heading and rate of descent along the ILS beam. If instruments are provided which allow the pilot to monitor the aircraft position relative to the ILS beam, this technique fulfills the systems design considerations outlined in Chapter 13. The pilot's responsibilities are limited to monitoring the automatic system, controlling airspeed, searching outside the aircraft for visual references, and then taking over control in the final stage of the approach.

Some of the integrated display systems in the developmental stage, or now coming into use, utilize other means of simplifying the operator's task. A common feature is the integration of cross-pointer steering commands, supplied by a flight director computer, with pitch-roll attitude indications in a single instrument. In these applications, the steering command indications derived from the computer indicate to the operator the corrections required to make asymtotic approaches to the localizer and glide paths. The steering command indications are a combination of several separate factors. The typical computer combines the radio course error signal with the heading error (first derivative) to determine the bank angle (second derivative) necessary to achieve the required correction. The steering indicator is centered by the operator by controlling the bank angle. The operator's task is greatly simplified, with minimum lag in reading off the adequacy of corrections. One difficulty is that, while keeping the pointers zeroed is relatively easy, the pilot cannot estimate how great his deviations from the beam actually are unless the radio error signals are displayed on another instrument. Without additional information, he must follow the director signals without knowing his actual flight path relative to the beam.

A point that should be mentioned concerning integrated displays of attitude and flight director information has to do with the display principles employed. In some cases, attitude indication is by means of a moving aircraft symbol, thus employing the aircraft-reference principle. Within the same display, however, the cross-pointer indications are based on the earth-reference principle (cross pointers represent position of beam rather than of aircraft). It was pointed out in Chapter 13 that for standard horizon and cross-pointer indicators, the experimental evidence shows superior performance with displays employing the aircraft-reference principle. Although no experimental

tests are available that show the result of mixing the two types of indication within a single integrated instrument there would appear to be the possibility of confusion and reversal errors, even for experienced pilots. This is certainly an area in which further research is needed.

A critical phase occurs during an instrument approach when the pilot must look outside the cockpit to establish visual reference with the runway. He has less time to scan his instruments, and must shift from one frame of reference to another, often alternating between the two. Automatic approach equipment can be used to assist the pilot so that he can devote more time and attention to searching for ground objects and establishing the ground plane. Other means of aiding the pilot during the transition phase are also possible.

It was pointed out in Chapter 10 that the time required for accommodation is an important factor in looking at the instrument panel and then at a distant object. Accommodating for near objects and then relaxing accommodation to focus for distant objects and returning to the near object may require up to a full second, far longer than the associated eye movement time. One means of reducing the time required for accommodation would be to project the more important instruments upon the lower portion of the windshield so that they are focused at optical infinity. If the three or four instruments employed most often in GCA and ILS approaches were projected in this way, the experimental data on eye fixations show that, at most, an occasional glance within the cockpit, with change of accommodation, would be required. Although this technique has not been employed for instrument landing, an experimental periscope design has been reported[14-11] which incorporates four optically projected flight instruments in the periscope field of view.

An experimental instrument landing display has been designed [14-2] to simplify transition from instruments to ground reference. The information required to close and hold the approach beam is analyzed and related to the kinds of information that the pilot has available when he comes into visual contact with the runway. The design attempts to facilitate the transition from instrument to visual approach by use of an instrument display that presents its information in a form similar to that obtained from the ground itself. The requirements of the display are based on a geometric analysis of how the ground information is utilized. The position and rate of movement of cross pointers are used to indicate angular displacement, rate of closure, and change of rate of closure to the localizer and glide-path planes.

Two aspects of this design deserve further comment. First, it should be noted that the instrument presents as independent indications the basic position error and the first and second derivatives which are combined in flight director indicators. Unfortunately, there is no available experimental evidence concerning the effectiveness with which this information is utilized when presented within a single display. Secondly, although the design attempts to simulate some aspects of the visual picture of the runway available to the pilot under visual conditions, the display is essentially symbolic.

Pictorial Displays for Instrument Approach and Landing

It has been reported [14-9] that the use of pictorial displays for instrument approach and landing is one of the applications for which pictorial presentations appear suitable and possibly superior to symbolic displays. On the basis of an analysis of the information needed by the pilot during his approach and the related visual cues, this report points out the difficulties of pictorially simulating all the qualities of the visual situation. It is concluded, however, that the pilot's performance and confidence might be improved by a successful pictorial display.

At the present time the only pictorial display development effort designed for instrument approach and landing is the joint ONR-BuAer-Army display that is described in Chapter 13. The success of this attempt to improve the ease and safety of instrument landing cannot be evaluated until results of the experimental tests are available.

MAPS AND CHARTS

In many current aircraft, maps and charts must still be used. Unfortunately, maps and charts have become more cluttered and there is a wider variety of them, because of the increasing complexity of flight. In part, the task of navigation is extremely difficult simply because so many charts must be carried, stowed, and handled on each flight. Their large size makes handling very awkward. When the charts are being read, the overprinting of electronic facilities makes the charts difficult to interpret.

The first step in a program 14-1, 14-7, 14-10, 14-13, 14-19 attempting to improve charts was to set up certain criteria that aeronautical charts must fulfill to be adequate for use in modern high-performance aircraft. First, the information appearing on the chart should be appropriate to the conditions of flight. Secondly, the data should be organized on the chart for maximum efficiency of use. The presentation should allow for maximum legibility (i.e., good symbols, type style and size, and good color). The chart size should be small enough for easy handling, and the scale should be suited to the speed and altitude of flight. Finally, the chart should be integrated with other types of navigation data systems.

A prototype chart was developed under the program mentioned above having the following characteristics:

1. Small dimensions to facilitate handling in the cockpit comfortably, yet drawn to show an area approximately equivalent to the fuel range of the aircraft (assumed, for this purpose, to be single-seat jets)

2. Separation of facilities for visual and instrument flight (electronic facilities on reverse of chart)

3. Only items presumed to be visible from high altitude (Unfortunately, very few tests have been undertaken to demonstrate what can be seen from aircraft at high altitudes.)

4. Only items which are presumed to be the type used by pilots for making fixes (A job analysis to determine whether pilots actually look at such objects in order to navigate is in order here.)

5. Items spaced at 150-mile intervals to provide check points every 15 to 20 minutes

6. Changes in elevation shown by shading

7. Pictorial symbols rather than symbolic ones

8. Color to differentiate certain classes of information such as cities and radio facilities

9. Minimum type size of eight points

A tabular navigation chart was also prepared, since radio techniques are used 90 percent of the time in high-performance aircraft; little can be seen from an altitude of 40,000 feet, unless meteorological conditions are favorable.

The next part in the development of adequate high-altitude charts under the program was to evaluate the two types of charts described above. The evaluation procedures included readability tests under daylight and night conditions and questionnaires designed to determine the pilots' opinions about which chart they preferred. The results indicated that both experimental charts tested were superior to the World Aeronautical Chart in presenting information for cross-country flights in jet aircraft.

Recommendations for further improvement of navigation charts for high-performance aircraft resulting from the development program are as follows: For airports: (1) show only those which have jet-aircraft landing facilities; (2) represent airports by means of symbols which duplicate the runway patterns; (3) use colors which provide good contrast between airport symbols and their background under low-level red illumination; and (4) place data notes close to their related objects. For radio facilities: (1) represent radio ranges, beacons, stations, etc., with symbols which are easily distinguished from each other; (2) make all symbols large enough to be perceived quickly, even under low-level red illumination; (3) use colors that provide good contrast between radio symbols and their background under low-level red illumination; and (4) use different colors for radio as compared to airport information. For natural and cultural items: (1) represent city areas so that they stand out from their background; (2) print names of cities in bold, black type against a pale background; (3) use shading to depict mountainous terrain; and (4) use symbols which differentiate between roads and railroads. In general: (1) use charts smaller in size and scale than the traditional World Aeronautical Chart; (2) make mileage scale readable from either end of the front and back of chart;

(3) print information in a type face which is large and bold enough to be read easily under low-level red illumination; (4) undertake a job analysis to determine what information pilots find necessary and useful for jet navigation; (5) do more research to determine optimum chart colors; and most important of all (6) confirm empirically the theoretical findings on visibility of objects from high-performance aircraft.

It is interesting to note the character of the fifth recommendation given just above -- more work is needed on color for charts. In much of the work during the 1940's, the principal consideration was the problem of illumination in relation to dark adaptation. The majority of these sources advised red lighting if the illumination intensity was kept at the minimum needed to read the smallest print on the chart. The difficulty of reading charts under low-level red illumination is well known. How can one design all-purpose charts to minimize this difficulty? A relatively early modification was the change from red ink, which disappears under red light, to magenta, which is fairly good under red light for navigational overprinting. Most of the other occasional changes in more recent years which have served to improve red light legibility have been minor or incidental to some other goal. However, a study [14-3] leading from a research program [14-4, 14-5, 14-6, 14-12] has been directed at the more specific problems of red light legibility. Red cockpit light has two characteristics which contribute difficulty: (1) restricted wave length range, and (2) low intensity. The first characteristic destroys the effect of color coding, and the second accentuates problems of discriminating fine detail or small brightness differences. The information normally conveyed by color coding has to be shown under red light by such devices as brightness differences, texture differences, and distinctive outlines. Overprinting is differentiated from its background by means of a brightness difference only; for small type under low illumination, the brightness difference must be large and the type must be of optimal design.

Assuming red light filtered in accordance with the specifications for the C4A cockpit lamp filter, and an illumination level a little below 0.1 foot-candle, a recent report [14-3] suggests that legibility be increased by the means listed below.

In regard to general appearance:

1. A somewhat different appearance under red light from that under white light, with resulting shifts in emphasis, is to be expected. Design of the chart should be such that under red light those features will be emphasized which are more useful for night flying.

2. The red light aspect of the chart should be compatible with the daylight aspect in all important respects. If under daylight the elevation levels show a systematic color progression, under red light they should show a systematic density progression.

In regard to area tints, the use of area tints can be modified in a number of ways to improve legibility under red cockpit light.

1. Other things being equal, tints of higher red light reflectance should be chosen in preference to those of lower reflectance.

2. If tints of different densities are required, as in the hypsometric scale, they should be assigned in such a way that the lighter tints fall where overprinting is most likely to be concentrated.

3. The densest area on a chart should have a red light reflectance of not less than 50 percent. Assuming a reflectance of about 5 percent for small type in dark blue or black ink, this provides a difference in reflectivity of 45 percent of the full scale.

4. If two features are shown in the same region by overlapping area tints, as elevations and control zones or control zones and range legs, it is difficult if not impossible to adjust the densities so that the legibility gap for overprinting will be maintained and the area tints will also be easily discriminable. Therefore, such overlap should be avoided.

In regard to overprinting, overprinting can be varied within some limits in density of ink, position, and details of letter design.

1. Lettering should be in black or dark blue unless considerably larger than 6-point capitals.

2. When a choice is possible, position of lettering should be adjusted to accomplish two things:

a. To put the lettering on the lightest available background

b. To minimize interference from grid lines, streams, railroads, etc., as this kind of interference impairs legibility more under low than under high illumination

3. Among the characteristics of type likely to affect legibility are size, case, letter-width, stroke-width, and letter spacing.

a. Size is the most critical of these characteristics under conditions of poor visibility. So far as possible, type should be no smaller than 6-point capitals in regular letter-width. The most nearly comparable lower case size is 8-point. Condensed letter-widths are less legible than regular letter-widths in either capitals or lower case. The measured height of letters in a given point size will vary from one kind of type to another. For precision, therefore, actual measurements should be used. The term "6-point capitals" as used here is intended to designate letters about 0.064 inch high.

b. Medium stroke-width and medium to wide letter spacing are usually optimal.

4. Type sizes and styles are used for coding. So far as possible, the coding arrangements should be coordinated with legibility conditions to minimize the arbitrary use of particular kinds of type in unfavorable situations

In regard to symbols, for discriminability of symbols under red cockpit light, some conditions can be indicated on the basis of present knowledge.

1. Contrast should be maximal as with lettering.

2. Shape should be distinctive in general outline, not in fine detail.

3. Minimum size should be determined, not by over-all dimensions, but by discriminability of smallest component that has to be recognized.

4. The design of symbols should be investigated more fully in relation to their psychological functions and conditions of use. Red cockpit light, with the attendant poor visibility, is one of the important conditions of use

Two experimental charts (a modification of the World Aeronautical Chart and an experimental radio facility chart) were constructed[14-3] to illustrate the principles noted above and to demonstrate techniques that might be used to increase legibility under low-level, red cockpit light.

LIST OF REFERENCES

14-1 Bishop, E. W., Waters, R. H., and Orlansky, J., Specifications for a Navigation Chart for Use in High-speed, High-altitude Aircraft. (Experimental chart XDA). ONR Contract No. N8onr-641. May 29, 1951.

14-2 Calvert, E. S. Report No. EL. 1478. Royal Aircraft Establishment, Farnborough, England. February 1953. (CONFIDENTIAL)

14-3 Crook, Mason N., Hanson, John A., and Weisz, Alexander, Aeronautical Charts under Red Light. WADC Tech. Report 54-198. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. May 1954.

14-4 Crook, M. N., Hanson, J. A. and Weisz, A., The Legibility of Type as Determined by the Combined Effect of Typographical Variables and Reflectance of Background. WADC Tech. Report 53-441. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. March 1954.

14-5 Crook, M. N., Hanson, J. A., and Weisz, A., Legibility of Type as a Function of Stroke-Width, Letter-Width, and Letter Spacing under Low Illumination. WADC Tech. Report 53-440. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. March 1954.

14-6 Crook, M. N., Hanson, J. A., and Wulfeck, J. W., The Legibility of Type as a Function of Reflectance of Background under Low Illumination. WADC Tech. Report 52-85. Wright Air Development Center. Wright-Patterson Air Force Base, Ohio. June 1952.

14-7 Dunlap and Associates, Inc. Summary Report and Survey of the Development of Graphic Aids (1950-1951). ONR Contract No. N8onr-641. October 1, 1951.

14-8 Ellis, W. H. B., Great Britain, FPRC 841. August 1953. p. 17. (CONFIDENTIAL)

14-9 Grether, W. F., Discussion of Pictorial Versus Symbolic Aircraft Instrument Displays. TSEAA-694-8B. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. August 4, 1947.

14-10 Kishler, J. P., Waters, R. H., and Orlansky, J., The Development of Graphic Aids to Air Navigation. ONR Contract No. N8onr-641. May 29, 1951.

14-11 Marg, E., Aircraft Periscopes for Pilotage and Search. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. November 1952. (CONFIDENTIAL)

14-12 McLaughlin, S. C., Jr., The Design of Aeronautical Charts for Use under Red Light. I. A Colorimetric Analysis. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. February 1951.

14-13 Murray, J. E., Waters, R. H., and Orlansky, J., An Evaluation of Two Experimental Charts Designed for Navigation in High-Speed, High-Altitude Aircraft. ONR Contract No. N8onr-641. Dept. of the Navy. May 15, 1952.

14-14 Payne, T. A., A Study of the Moving Figure and Orientation of Symbols on Pictorial Aircraft Instrument Displays for Navigation. Tech. Report SDC 71-16-6. U. S. Navy, Special Devices Center, Port Washington, N. Y. July 1950.

14-15 Roscoe, S. N., Smith, J. F., Johnson, B. E., Dittman, P. E., Williams, A. C., Comparative Evaluation of Pictorial and Symbolic VOR Navigation Displays in the 1-CA-1 Link Trainer. National Research Council, Civil Aeronautics Administration, Div. of Research, Committee on Aviation Pyschology and University of Ill. Report No. 92. October 1950.

LIST OF REFERENCES (Cont)

14-16 Setzer, L. E., The Type III Portable Pictorial Computer. Part I. Development and Initial Tests. Tech. Development Report No. 172. C.A.A., Technical Development and Evaluation Center, Indianapolis, Ind. October 1952.

14-17 Setzer, L. E., The Type IV Rotatable-Panel Pictorial Computer. Part I. Development and Initial Flight Tests. Tech. Development Report No. 195. C.A.A., Technical Development and Evaluation Center, Indianapolis, Ind. April 1954.

14-18 Setzer, L. E., and Leake, P. H., The Type V Pictorial Computer with Automatic Chart Selection. Part I. Development and Initial Tests. Tech. Development Report No. 199. C.A.A., Technical Development and Evaluation Center, Indianapolis, Ind. June 1954.

14-19 Waters, R. H., and Orlansky, J., The Use of Mathematical and Meteorological Data in Aeronautical Chart Construction. ONR, Contract No. N8onr-641. May 29, 1951.

14-20 Williams, A. C., Jr., and Roscoe, S. N., "Evaluation of Aircraft Instrument Displays for Use with the Omni-Directional Radio Range (VOR)." J. Appl. Psychol. Vol. 34. 1950. pp. 123-130.

GENERAL BIBLIOGRAPHY

14-21 Anon. Experiments in the Design of the Four Basic Types of Map Symbols. Yale University Cartographic Lab., New Haven, Conn. Nonr-60903, Annual Progress Report for period ending January 1, 1954.

14-22 Anon. Multiplex Mapping. Dept. of the Army, Washington 25, D. C. Tech. Manual 5-244. June 1954.

14-23 Ayer, R. W., and White, F. C., Development of an Airborne Radar Method of Avoiding Collisions with Terrain, Aircraft and Other Obstacles. American Airlines System, Operational Development Branch, New York, N. Y. September 1949.

14-24 Baird, R. S., Evaluation of Precision Approach Radar. Tech. Note No. WCT 52-67. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. December 1950.

14-25 Christensen, Julien M., Quantitative Instrument Reading as a Function of Dial Design, Exposure Time, Preparatory Fixation, and Practice. Tech. Report 52-116. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. September 1952.

14-26 Christensen, J. M., Psychological Factors Involved in the Design of Air Navigation Plotters. Aero Medical Lab., Headquarters, Air Materiel Command, Engineering Div., Wright Field, Dayton, Ohio. TSEAA-694-1D. December 1946.

14-27 Clark, B., and Graybiel, A., Disorientation: A Cause of Pilot Error. BuMed & Surg. Research Report No. NM 001 110 100.39. U. S. Naval School of Aviation Medicine, Pensacola, Fla. March 1955.

14-28 Clark, B., and Nicholson, Marjorie A., Aviators' Vertigo: A Cause of Pilot Error in Naval Aviation Students. Project NM 001 059-01.37. U. S. Naval School of Aviation Medicine, Pensacola, Fla. August 1953.

14-29 Clementson, G. C., Doughty, J. M., Huggins, W. H., Seeger, C., Smith, C. C., Williams, A. C., Jr., Wray, J., and Licklinder, J. C. R., HFORL Memo. No. 41. HFORL, Bolling Air Force Base, Washington, D. C. December 1953. (CONFIDENTIAL)

14-30 Coakley, J. D., Thomas, L. L., Horwath, J. F., Kernan, J. P., and Lenzycki, H. P., Training Equipment, Instrument Flying under Simulated Instrument Conditions. WADC Tech. Report 6431. Wright-Patterson Air Force Base, Dayton, Ohio. October 1953.

14-31 Collins, H. R., Methods of Indicating Aircraft Heading. WADC, Aero Medical Laboratory, Dayton, Ohio. RDO 694-31E, Tech. Note 52-65. September 1952.

14-32 Connell, Shirley C., Some Variables Affecting Instrument Check Reading. U. S. Air Forc Tech. Report No. 6024. Air Materiel Command, Aero Medical Laboratory E. O. No. 694-27. August 1950.

14-33 Conrad, R., Speed and Load Stress in a Sensorimotor Skill. Great Britain, Medical Research Council, Applied Psychology Research Unit, A. P. U. 134/50, Psychological Laboratory, Cambridge, Mass. Autumn 1950.

14-34 Crampton, G. H., and Young, F. A., "The Differential Effect of a Rotary Visual Field on Susceptibles and Nonsusceptibles to Motion Sickness." J. Compar. Physiol. Psychol. Vol. 46. December 1953. pp. 451-453.

14-35 Crook, Mason N., Printed Materials, Maps and Charts. Tufts University. 1949.

14-36 Crook, M. N., Hanson, J. A., and Weisz, A., Aeronautical Charts under Red Light. WADC Tech. Report 54-198. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. May 1954.

14-37 Crumley, L. M., Human Engineering Investigation of Aircraft Cockpit Visual Displays: Rotating Dial for Five Inch Compass Indicator. Part II. Experimental Dial Type Specification for Five Inch Compass Indicators. Rep. TED NAM AE-7047.1, Top... al Repo: XG-T-203. Naval Air Materiel Center, Naval Air Experimental Station, Philadelphia, Pa. December 1953.

14-38 ten Doesschatte, G., and Lansberg, M. P., "Time Consumption in Eye Movements." Ophthalmologica. Vol. 128. 1954. pp. 298-300.

14-39 Felton, W. W., Fritz, E., and Grier, G. W., Air-Ground Communications in Terminal Air Traffic Control. Report F-2185-1. Franklin Inst., Laboratories for Research and Development, Philadelphia, Pa. March 1953.

14-40 Fitts, Paul M., Jones, Richard E., and Milton, John L., "Eye Movements of Aircraft Pilots during Instrument-Landing Approaches." Aero. Engng. Rev. Vol [illegible]. February 1950. pp. 1-6.

14-41 Fitzpatrick, R. F., Study and Development of Equipment for Simulating Blind Flying. SDC Tech. Report 37003-5. June 30, 1949.

14-42 Fleishman, E. A., The Perception of Body Position -- Effect of Speed, [illegible] and Direction of Displacement on Accuracy of Adjustment to an Upright Po[illegible]. Project 509-020-0003, Research Bull. 53-1. USAF, HRRC, Air Training Command, Lackland Air Force Base, San Antonio, Texas. January 1953.

14-43 Fleishman, E. A., "Perception of Body Position in the Absence of Visual Cues." J. Exp. Psychol. Vol. 46. 1953. pp. 261-270.

14-44 Forbes, A., U. S. Navy, BuMed & Surg[illegible] Project A. January 7, 1945. (CONFIDENTIAL)

14-45 French, R. S., "Identification of Dot Patterns from Memory as a Function of Complexity." J. Exp. Psychol. Vol. 47. 1954. pp. 22-26.

14-46 French, R. S., "Pattern Recognition in the Presence of Visual Noise." J. Exp. Psychol. Vol. 47. 1954. pp. 27-31.

14-47 French, Robert S., The Accuracy of Discrimination of Dot Patterns as a Function of Angular Orientation of the Stimuli. Human Resources Research Center Research Bull. 53-3. March 1953.

14-48 French, Robert S., "The Discrimination of Dot Patterns as a Function of Number and Average Separation of Dots." J. Exp. Psychol. Vol. 46. 1953.

14-49 Garvey, W. D., and Knowles, W. B., "Response Time Patterns Associated with Various Display-Control Relationships." J. Exp. Psychol. Vol. 47. 1954. pp. 315-322.

14-50 Gebhard, J. W., Visual Display of Complex Information. 1949.

14-51 Gebhard, J. W., U. S. Navy, Office of Naval Research, Special Devices Center Report 166-I-53. September 15, 1948.

14-52 Gebhard, J. W., U. S. Navy, Office of Naval Research, Special Devices Center Report 166-I-46. August 1, 1948.

14-53 Gebhard, J. W., de Groot, S. G., and Glickman, R. W., The Interpretability of Plotted Information on Polar-Coordinate Displays. ONR Project Designation NR 507-470, Report 166-I-152. July 1952.

14-54 Gebhard, J. W., and Glicken, R. W., Some Perceptual Problems in the Design of Coded Switching Keyboards. ONR, Special Devices Center, Project Designation NR 784-001, SDC Project 20-F-I, Tech. Report 166-I-126. October 1951.

14-55 Gerathewohl, S. J., and Strughold, H., "Time Consumption of Eye Movements and High-Speed Flying." USAF School of Aviation Medicine, Randolph Field, Texas. J. Aviat. Med. Vol. 25. 1954. pp. 38-45.

14-56 Graham, Norah E., "Manual Tracking on a Horizontal Scale and in the Four Quadrants of a Circular Scale." FPRC 783, Flying Personnel Research Committee, University of Durham, Nuffield Dept. of Industrial Health, Brit. J. Psychol. Vol. 43. 1952. pp. 70-77.

14-57 Grether, W. F., "Instrument Reading. I. The Design of Long-Scale Indicators for Speed and Accuracy of Quantitative Readings." J. Appl. Psychol. Vol. 33. 1949. pp. 363-372.

14-58 Grether, W., Design of Aircraft Switch Panels fo[illegible]m Ease of Checking of Switch Position. TSEAA-694-4F. AAF, Air Materiel Command, Aero Medical Lab., Wright Field, Dayton, Ohio. April 1947.

14-59 Grether, W. F., and Connell, Shirley C., Psychological Factors in Check Reading of Single Instruments. MCREXD-694-17A. USAF, Air Materiel Command, Aero Medical Lab., Engineering Div., Wright Field, Dayton, Ohio. September 1948.

14-60 Hake, H. W., and Eriksen, C. W., Effect of the Number of Permissible Response Categories on the Learning of a Constant Number of Visual Stimuli. Tech. Report 54-163. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. April 1954.

GENERAL BIBLIOGRAPHY (Cont)

14-61 **Jones, R. E., Milton, J. L., and Fitts, P. M.**, An Investigation of Errors Made by Pilots in Judging the Attitude of an Aircraft without the Aid of Vision. Memo Report TSEAA-8/FMF/paw, Serial No. TSEAA-694-13. AAF Air Materiel Command, Wright Field, Dayton, Ohio. May 1947.

14-62 **Katz, Milton S., and Spragg, S. D. S.**, "Tracking Performance as a Function of Frequency of Course Illumination." J. Psychol. Vol. 40. 1955. pp. 181-191.

14-63 **Kaufman, E. L., Reese, T. W., Volkmann, J., and Rogers, S.**, Accuracy, Variability and Speed of Adjusting an Indicator to a Required Bearing. Special Devices Center Report 166-I-MHC 4. September 2, 1947.

14-64 **Klemmer, E. T., and Muller, Paul F.**, The Rate of Handling Information: Key Pressing Responses to Light Patterns. U. S. Air Force, Air Research and Development Command, Human Factors Operations Research Laboratories, Report No. 34. March 1953.

14-65 **Knowles, W. B., and Newlin, E. P.**, Coding by Groups as a Mode of Stimulus Presentation. Project NR 592-030, NRL Project Y02-03. Naval Research Lab., Washington, D. C. September 1955.

14-66 **Koponen, Arthur, Waters, Rolland H., and Orlansky, Jesse**, The Associational Value of Aeronautical Chart Symbols. Office of Naval Research, Dunlap and Associates. Report No. 641-05-7. July 1952.

14-67 **Kraft, Conrad L., and Fitts, Paul M.**, A Broad-Band Blue Lighting System for Radar Air Traffic Control Center. WADC Tech. Report 53-416. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. January 1954.

14-68 **Loucks, R. B.**, The Interpretation of Azimuth Indicators by Novices: II. Aircraft Indicators with Full-Scale Azimuth Cards that Turn. E.O. No. 694-19, AF Tech. Report 5965. USAF, Air Materiel Command, Wright-Patterson Air Force Base, Dayton, Ohio. March 1950.

14-69 Loucks, R. B., An Experimental Comparison of the Relative Effectiveness with which Two Types of Map Reading Procedures can be Utilized by Novices. AF Tech. Report 5963. USAF, Air Materiel Command, Wright-Patterson Air Force Base, Dayton, Ohio. October 1949.

14-70 Loucks, R. B., An Analysis of the Types of Errors Made by Novices in Interpreting Azimuth Indicators when the Bearings are Administered Verbally. AF Tech. Report No. 5958. USAF, Air Materiel Command, Wright-Patterson Air Force Base, Dayton, Ohio. October 1949.

14-71 Loucks, R. B., Evaluation of Aircraft Attitude Indicators on the Basis of Link Instrument Ground Trainer Performance. Project No. 341, Report No. 1. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. June 22, 1945.

14-72 Loucks, Roger B., Legibility of Aircraft Instrument Dials: The Relative Legibility of Manifold Pressure Indicator Dials. Project Report No. 325, Report No. 1. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. December 7, 1944.

14-73 Loucks, Roger B., Legibility of Aircraft Instrument Dials: The Relative Legibility of Various Climb Indicator Dials and Pointers. Project Report No. 288, Report No. 1. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. November 25, 1944.

14-74 Loucks, Roger B., Legibility of Aircraft Instrument Dials: A Further Investigation of the Relative Legibility of Tachometer Dials. Project No. 265, Report No. 2. U. S. Air Force School of Aviation Medicine, Randolph Field, Texas. October 27, 1944.

14-75 Mangelsdorf, John E., Variables Affecting the Accuracy of Collision Judgments on Radar-Type Displays. Tech. Report 55-462. Wright Air Development Center, Aero Medical Lab. 1955.

14-76 Milton, John L., McIntosh, Billy B., and Cole, Edward L., Fixations During Day and Night GCA Approaches Using an Experimental Instrument Panel Arrangement. U. S. Air Force Tech. Report No. 6709, RDO No. 694-31. Wright Air Development Center. February 1952.

14-77 Milton, John L., McIntosh, Billy B., and Cole, Edward L., Eye Fixations of Aircraft Pilots. VI. Fixations During Day and Night ILAS Approaches Using an Experimental Instrument Panel Arrangement. U. S. Air Force Tech. Report No. 6570. RDO No. 694-31 and 694-28. Wright Air Development Center. October 1951.

14-78 Milton, John L., and Wolfe, Fred J., Fixations During Zero-Reader Approaches in a Jet Aircraft. WADC Report 52-17, RDO No. 694-31. Wright Air Development Center. February 1952.

14-79 Noble, Rosalie, Human Engineering Investigation of Aircraft Cockpit Visual Display: Fuel Quantity Presentation. Report TED NAM AE-7047.7, Report XG-T-243. Naval Air Material Center, Naval Air Experimental Station, Philadelphia, Pa. February 1955.

14-80 Noble, Rosalie, Human Engineering Investigation of Aircraft Cockpit Visual Display: Dial Design for Mach-Airspeed Indicator. Report NAM AE-7047.5, Topical Report XG-T-237. Naval Air Materiel Center, Naval Air Experimental Station, Philadelphia, Pa. December 1954.

14-81 Norris, Eugenia B., and Spragg, S. D. S., "Performance on a Following Tracking Task (Modified SAM Two-Hand Coordination Test) As a Function of the Relations between Direction of Rotation of Controls and Direction of Movement of Display." J. Psychol. Vol. 35. 1953. pp. 119-129.

14-82 Norris, E. B., and Spragg, S. D. S., Studies in Complex Coordination. II. Performance of the Two-Hand Coordinator as a Function of the Relations between Direction of Rotation of Controls and Direction of Movement of Display. Special Devices Center Report 241-6-5. Office of Naval Research. November 1950.

14-83 Nygaard, J. E., and Roscoe, S. N., Manual Steering Display Studies. I. Display-Control Relations and the Configuration of the Steering Symbol. Tech. Memo 334. Hughes Aircraft Company. October 1, 1953.

14-84 Payne, T. A., A Study of the Moving Part, Heading Presentation, and Map Detail on Pictorial Air Navigation Displays. SDC Report 71-16-10. Office of Naval Research. November 1952.

14-85 Peterson, John H., and Simonson, Ernst, "The Effect of Glare on the Accommodation Near Point." Amer. J. Ophthal. Vol. 34. 1951. pp. 1088-1092.

14-86 Pinson, E. A., Maps, Charts, and Photographs, Fluorescent and Tonal Keyed for Red Light. U. S. Army Air Forces, Materiel Center, Experimental Engineering Section. September 17, 1942.

14-87 Pinson, E. A., Romejko, Walter J., Chapanis, A., and Rouse, Richard O., Visual Factors Relating to the Design and Operation of Aircraft. Tech. Note, Ser. No. TSEAL 3-2. U. S. Army Air Forces, Air Technical Service Command, Engineering Div. June 7, 1945.

14-88 Poulton, E. C., Two Pointer and One Pointer Displays in Tracking. Great Britain, Medical Research Council. A.P.U. 142/50. Applied Psychol. Research Unit, Cambridge. December 1950.

14-89 Reese, T. W., Volkman, J., Rogers, S., and Kaufman, E. L., Special Problems in the Estimation of Bearing. Special Devices Center Report 166-I-MHC 2, Johns Hopkins University. January 1948.

14-90 Riggs, Lorrin A., The Development of a Counter or Odometer Type Scale to Replace the Micrometer Scale of the Panoramic Telescope M12. U. S. Office of Scientific Research and Development, National Defense Research Committee, O.S.R.D., No. 4390, Project SOS-11. November 28, 1944. Tufts College.

14-91 Rogers, S., Volkman, J., Reese, T. W., and Kaufman, E. L., Accuracy and Variability of Direct Estimates of Bearing from Large Display Screens. Special Devices Center Report 166-I-MHC 1. Office of Naval Research. May 15, 1947.

14-92 Scher, S. H., Pilot's Loss of Orientation in Inverted Spins. National Advisory Committee for Aeronautics. Tech. Note 3531. (Langley Aeronautical Laboratory, Langley Field, Virginia.) October 1955.

14-93 Senders, John W., Tracking with Intermittently Illuminated Displays. Aero Med. Lab. Tech. Report 55-378. Wright Air Development Center. 1955.

14-94 Simon, Charles W., Instrument-Control Configurations Affecting Performance in a Compensatory Pursuit Task. U. S. Air Force Tech. Report No. 6015. Wright Air Development Center. February 1952.

14-95 Sleight, R. B., and Mowbray, G. H., "Discriminability between Geometric Figures under Complex Conditions." J. Psychol. Vol. 31. 1951. pp. 121-127.

14-96 Vernon, Magdalen D., "The Visual Presentation of Factual Data." Brit. J. Educ. Psychol. Vol. 20. November 1950. pp. 174-185.

14-97 Vince, M. A., Learning and Retention of an "Unexpected" Control Display Relationship under Stress Conditions. Great Britain, Medical Research Council A.P.U. 125/50, Applied Psychol. Research Unit, Cambridge, Mass. August 1950.

14-98 Wapner, S., Werner, H., and Chandler, K. A., "Experiments on Sensory-Tonic Field Theory of Perception: I. Effect of Extraneous Stimulation on the Visual Perception of Verticality." J. Exp. Psychol. Vol. 42. 1951. pp. 341-345.

14-99 Wapner, S., Werner, H., and Morant, R. B., "Experiments on Sensory-Tonic Field Theory of Perception: III. Effect of Body Rotation on the Visual Perception of Verticality." J. Exp. Psychol. Vol. 42. 1951. pp. 351-357.

14-100 Warrick, M. J., and Greiner, W. F., The Effect of Pointer Alignment on Check Reading of Engine Instrument Panels. MCREXD-694-17. USAF, Air Materiel Command, Engineering Div., Wright-Patterson Air Force Base, Ohio. June 1948.

14-101 Warrick, M. J., and Lund, D. W., Effect of Moderate Positive Acceleration (G) on Ability to Read Aircraft-Type Instrument Dials. Memo Report TSEAA-694-10. Aero Medical Lab., Air Materiel Command, Wright-Patterson Air Force Base, Ohio. November 1946.

14-102 Watts, A. F. A., and Wiltshire, H. C., Investigation of Eye Movements of an Aircraft Pilot under Blind Approach Conditions. Note 26. College of Aeronautics, Cranfield, England. May 1955.

14-103 Werner, H., Wapner, S., and Bruell, J. H., "Experiments on Sensory-Tonic Field Theory of Perception: VI. Effect of Position of Head, Eyes, and of Object on Position of the Apparent Median Plane." J. Exp. Psychol. Vol. 46. 1953. pp. [illegible].

14-104 White, W. J., Warrick, M. J., and Grether, W. F., "Instrument Reading III: Check Reading of Instrument Groups." J. Appl. Psychol. Vol. 37. 1953. pp. 302-307.

14-105 Williams, A. C., and Roscoe, S. N., Pilot Performance in Instrument Flight as a Function of the Extent and Distribution of Visible Horizon. ONR, Special Devices Center. Project 20-L-1, Tech. Report SDC 71-16-3. June 1949.

14-106 Witkin, H. A., "Further Studies of Perception of the Upright when the Direction of the Force Acting on the Body is Changed." J. Exp. Psychol. Vol. 43. No. 1. January 1952. pp. 9-20.

14-107 Witkin, H. A., "Perception of the Upright when the Direction of the Force Acting on the Body is Changed." J. Exp. Psychol. Vol. 40. 1950. pp. 93-106.

14-108 Witkin, H. A., and Wapner, S., "Visual Factors in the Maintenance of Upright Posture." Amer. J. Psychol. Vol. 43. 1950. pp. 31-50.

14-109 Worchel, P., "The Role of the Vestibular Organs in Space Orientation." J. Exp. Psychol. Vol. 44. July 1952. pp. 4-10.

14-110 Youtz, R. P., and Flanagan, J. C., Audio Aids to Blind Flying and a Scoring Device for the Link Trainer. ONR, Special Devices Center. Tech. Report 370-2-1. July 1949.

CHAPTER 15

CATHODE-RAY TUBE INDICATORS AND THEIR USE IN INTERCEPTION AND BOMBARDMENT

This chapter reviews the physical factors affecting scope visibility, stressing the importance of scope brightness particularly, and recommending that the operator always be given the opportunity to adjust bias and video gain. Human factors in CRT visibility are also reviewed, with emphasis on the need for appropriate adaptation of the eye. At the end of the chapter, the use of CRT indicators in interception and bombardment is discussed rather fully.

CATHODE-RAY TUBE INDICATORS

Physical Factors Affecting Scope Visibility

Aircraft display instruments using cathode-ray tubes (CRT) usually belong to the general family of radar instruments. Two exceptions that should be noted are: (1) sometimes radar data go directly to a computer, with the scope presentation as the computer output; and (2) occasionally data are picked up through other media (such as infrared radiations) and fed either directly or via computer to the CRT display.

One family of visual problems is immediately apparent: the general problems of visibility of CRT displays. Regardless of the use to which the information is put, if it cannot be seen clearly enough to be understood, there is no point in displaying it. Considerable attention has been given to relating the basic attributes of human vision to the peculiarities of CRT displays, and we shall review the findings of such research.

Remembering that our present concern is simply with the visibility of the signal on the scope face, let us refer back to the basic data on human vision and consider the curves given in Chapter 8. These curves relate the principal physical factors that determine how readily we can distinguish an object from a background. The curves of Figure 8.12, Chapter 8, were computed on the basis of the contrast required for detection of the target in half of the trials (50 percent probability). These data[15-6] have been reworked for 99 percent probability of detection and are shown in Figure 15.1. The individual curves are for different target sizes expressed as target area in square minutes of visual angle.

The important variables are the size of the object and the contrast ($\Delta B/B$) between the brightness of the object and the brightness of the background. Note that the higher the background brightness and the bigger the object, the less contrast is required for the eye to distinguish an object. In other words, the eye is more efficient at detecting contrasts at high brightness levels than at low.

The physical factors that are important in determining cathode-ray tube visibility will be those that affect the size of the target and target-background contrast. Such factors include:

1. Cathode-ray tube bias
2. Pulse repetition frequency
3. Antenna rotation rate
4. Beam width
5. Pulse length
6. Target range
7. Scope noise
8. Scope size
9. Scope resolution
10. Ambient illumination

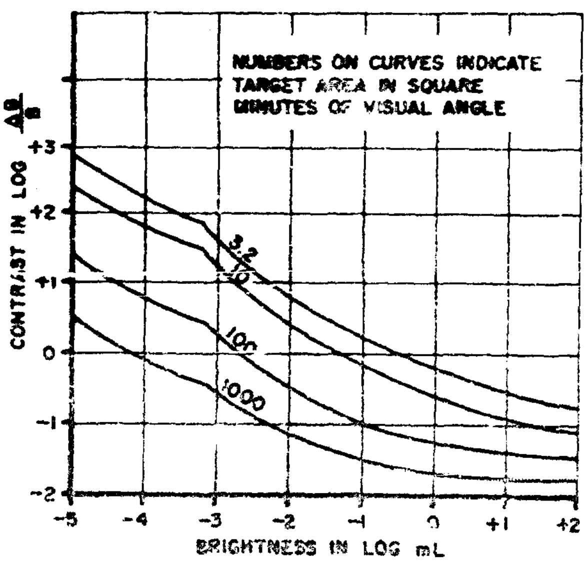


Figure 15.1 Contrast Discrimination as a Function of Brightness for Various Target Areas (from Baker & Grether[15-8])

These factors will be discussed below. Much of the information on physical factors affecting cathode-ray tube visibility has been reviewed and integrated[15-17] and the latter reference should be considered the source of information in the following discussion unless specific references are made to other sources. In addition, several human factors (conditions of the operator) serve to affect scope visibility. These factors will be discussed later.

Cathode-Ray Tube Bias

The single physical factor of greatest importance in determining signal visibility is the CRT bias, for this controls the background brightness against which a signal must be detected. Curves are shown in Figure 15.2 for various CRT bias values that are given as negative voltages with respect to the cathode. Each curve shows the signal strength (expressed as db attenuation with a reference level of 1 volt) necessary to attain various contrast values ($\Delta B/B$)* Since we consider a situation ideal for visibility or detectability when a weak signal will produce enough contrast to be seen, we equate weak signals (high attenuation) with high visibility or detectability. Note that less energy, thus weaker signal, is required for a given contrast value on dim scopes than on bright ones. So the efficiency of scopes is greatest at low backgrounds, while the eye is most efficient at high backgrounds.

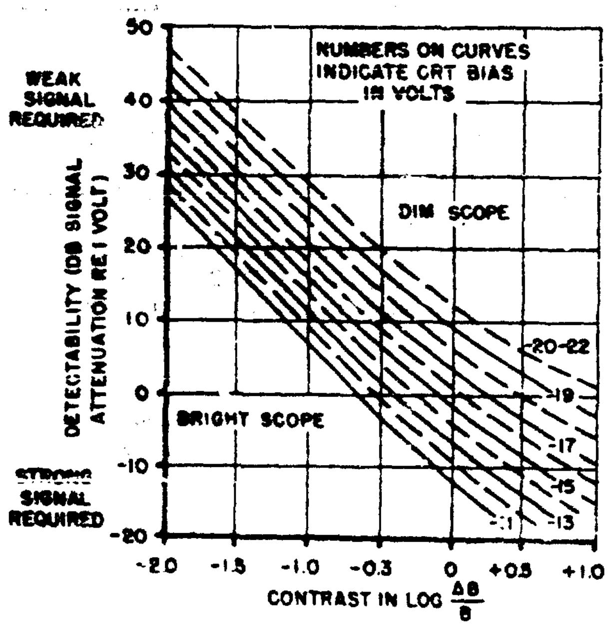


Figure 15.2 Detectability as a Function of Contrast, Plotted for Various Bias Voltages on Cathode-Ray Tube (after Morgan[15-17])

We may logically expect that, when we combine the characteristics of scopes and of the eye, we will find the optimum CRT bias for visibility to lie somewhere in the middle brightness area. Figure 15.3 verifies these expectations. For varying conditions of target size and phosphor decay, the optimum CRT bias should lie in the range -15 to -17 volts. Figure 15.3 gives a set of three curves for each of three target sizes. The three curves for each target size show bias-detectability relations for 1/6 second, 1 second, and 10 seconds of phosphor decay, these time lags being introduced to allow for delays in perception and detection in the human operator. These curves are theoretical functions, but experiments performed to determine optimum CRT bias have yielded startlingly similar curves.[15-21] The theoretical curves are given here to permit extension of interpretation and prediction beyond the conditions actually tested.

---

*The scope performance curves of Figures 15.2 and 15.3 are computed for the P-7 phosphor, an antenna rotation rate of 10 rpm, a pulse repetition frequency of 600 PPS, and a target 3 inches from the center of a 12-inch scope.

Although the data plotted in Figures 15.2 and 15.3 can be applied only to the conditions for which they were computed (see footnote, previous page), the relationships among the variables can be expected to hold for other scopes. So we can generalize that CRT bias, target contrast, target size, and delay of observation are important factors in target visibility.

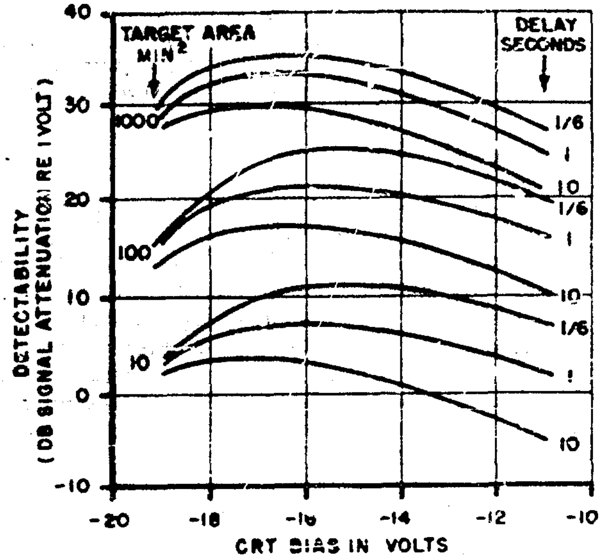


Figure 15.3 Detectability as a Function of Bias Voltage, for Various Target Areas and Perception Time Lags (after Morgan[15-17])

Pulse Repetition Frequency

Let us consider target brightness in a little more detail, for it determines contrast for any given background. The rate at which pulses are sent out, called pulse repetition frequency (PRF), determines how many echo signals will come back from the external target in a given amount of time. Thus the higher the PRF, the more returns per unit time will strengthen the cathode ray. These pulses will add up on the scope face to give a brighter target return. In general, an increase in PRF results in an increase in target detectability. The change in detectability is greater for a given rate increase at low frequencies (below 300 PPS) than it is at higher frequencies, and the effect is greater on dim scopes than on bright scopes. For the P-7 phosphor, at 1/6-second delay, at antenna rotation speeds of 5 and 10 rpm, and at -16 volts CRT bias (area of optimum bias), an increase of PRF from 450 to 1000 PPS gives about 5-db improvement in detectability. The same change in PRF at -11 volts (bright scope) has a negligible effect on detectability.

Antenna Rotation Rate

A second factor to be considered for its effect on target brightness is the rate of rotation of the antenna. Moving the scope sweep line has the effect of "spraying" the electrons of the cathode ray across the scope face, and, everything else being equal, the faster the spraying (higher rpm) the fewer the electrons hitting any particular spot on the scope face. This reduction in current density results in a weaker target. The effect of changing rotation speed on detectability is greater on dim scopes than on bright scopes and greater at lower pulse repetition frequencies than at higher ones. On the scope described in the preceding illustrations at a PRF of 600 PPS, changing antenna rotation rate from 5 rpm to 30 rpm causes a 7-db loss in detectability at a bias of -16 volts, and about 2-db loss at -11 volts bias. Changes in PRF and in antenna rotation speed do not change the optimum bias for detectability; they simply increase or decrease detectability at this bias.

Beam Width and Pulse Length

We have already seen that the size of the target on the scope face is important in determining its visibility (the bigger the target, the easier it is to see). The width of the beam of electrons in the tube (beam width) and the amount of time the signal pulse is emitted (pulse length) both contribute to the size of the spot on the screen. The effect of increases in either of these variables is an increase in detectability, the response being nearly linear over a wide range of target sizes.

Target Range

The farther the beam of electrons is deflected from the center of the scope (the greater the range depicted), the larger the size of the spot will be and the dimmer it becomes. This antagonistic combination of effects nearly counterbalances, although at optimum brightness the size function is a little more effective. There are about 1 or 2 db of improvement in theoretical detectability when the target moves from 1 inch to 6 inches from the center of the scope used in the previous examples.

Scope Noise

A scope face is generally cluttered with random undesired signals from various sources. This visual [illegible] on the scope adds to the background brightness and the signal brightness equally, the net effect being to reduce signal-to-background contrast. We have previously noted that cathode-ray tubes are more [illegible]

low background brightnesses than at high; so at dim levels the benefits from the added brightness supplied by noise overweigh the losses due to reduction in contrast. At higher brightnesses, the reverse is true. So a little noise is actually helpful for target visibility on dim scopes, whereas it is a definite drawback at higher intensity levels. Noise serves to shift the optimum CRT bias, since it contributes to the bias in a sense. So, if a noiseless scope had an optimum bias of -16 volts, with 2 volts noise the optimum bias would be -18 volts; that is, we make a dimmer setting to compensate for the brightness added by the noise. A complicating factor more difficult to analyze is the nature of the noise signals. If they differ greatly from the target signals, targets should still stand out well; but if they look like the target signals, then they will tend to mask them, decreasing detectability.

Scope Size

The size of a scope can be increased without any change in the size of signals -- that is, just to increase the area of coverage. Such a change would not affect the inherent visibility of signals. However, a change in scope size is usually accompanied by a proportionate change in signal size. In this case, we would expect the detectability of signals to improve with increasing size, and/or larger scopes to be of more advantage than smaller ones with regard to visibility. The same results would be obtained with optical magnification of the scope face. Experiments requiring operators to read data from scopes (usually range and bearing) have shown very little difference in accuracy between scopes ranging from 5 to 25 inches in diameter.[15-1] The general recommendation has been that a 6- or 7-inch scope is adequate when plotting on the scope face is not required.[15-22]

One compromise solution to size problems is to put a magnifying lens in front of the scope. This has been tried successfully with the APQ-13 and APQ-23 radars.[15-19] The magnifier was placed at the viewer's end of the shielding hood and effectively doubled the size of the scope presentation. It also had the advantages of increasing the apparent viewing distance from 8 to 16 inches and of increasing the apparent scope brightness, permitting lower gain settings.

Scope Resolution

The limit of resolution (ability to give two separate blips for two separate targets) on current radar equipment is well above the two-point threshold of the human eye.[15-6] In other words, even on small scopes, the eye is capable of perceiving much finer detail than the scope is capable of presenting. With improvements in radar resolution in the future, however, there may come a time when increasing scope size will be necessary to permit perception of all the details the equipment can reproduce.

Ambient Illumination

The ambient illumination of the area in which a cathode-ray tube is operating can affect scope visibility through two concurrent activities. First, light falling on the screen will be reflected in part, raising the general brightness of the scope if the light is diffuse or causing annoying highlights if specular. Second, the incident light acts in the same way as the cathode ray to stimulate the phosphor, adding another increment to the scope brightness. This combination of reflection and excitation is equivalent (as in the case of random noise) to raising the CRT bias, with a consequent loss of detectability at a given bias. The expected loss for the 1- and 10-second delay conditions of Figure 15.3 are shown in Figure 15.4 (dashed lines) for the case when the increment in brightness due to ambient illumination is equal to the light originally emitted from the scope. (The curve denoting the drop for 1 sec lag and 1000 sq min target area lies exactly over the original curve representing the 10 sec lag and 1000 sq min target area.) When the reflected illumination is high with respect to the original brightness, we need consider only the signal strength required to give the necessary contrast with respect to the reflected brightness -- that is, the effect of CRT bias is negligible.

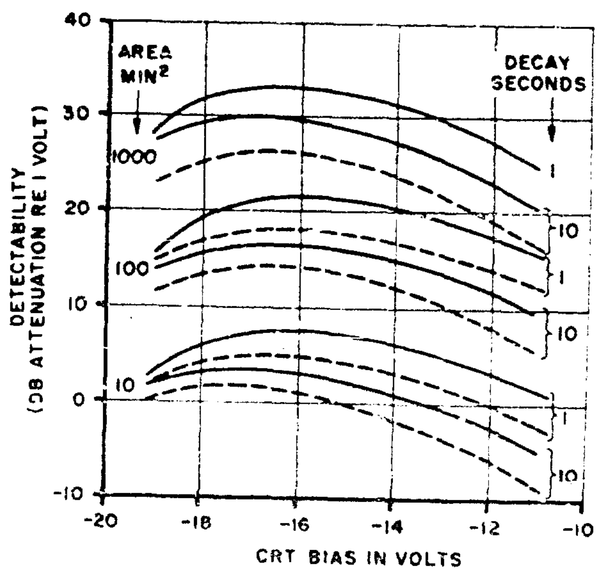


Figure 15.4 Detectability as a Function of Bias Voltage, Showing Losses Caused by Ambient Illumination (after Morgan[15-17])

The general rule given at present is to limit the increment contributed to scope brightness by ambient illumination of 25 percent or less of the original scope brightness[15-6]

In the aircraft, the pilot's or bombardier's work space must be used for a variety of visual tasks in addition to scope reading, and scope requirements cannot be used to determine the ambient illumination. Furthermore, ambient illumination varies considerably (such as in the difference in cockpit illumination between daytime and nighttime operations). Consequently, the scope face must be shielded in some way. The addition of a tube-like hood around the scope face or the installation of a small, heavy curtain that the operator can pull around him while using the scope are two of the means currently used for shielding airborne scopes.

A more complex method of shielding the scope from the effects of ambient illumination is the use of a combination of phosphor, filter on the scope, and ambient illumination such that the filter will absorb rather than reflect the ambient light, yet will transmit the kind of light emitted by the phosphor. Because of the various additional problems of cockpit and cabin illumination, this procedure has been applied to ground rather than airborne installation. However, because this system may be contemplated in future designs, Table 15.1 summarizes some of the more promising combinations that have been investigated.

Table 15.1 Summary Table of Lighting Systems[15-6]

Ambient Light Sources and Filters	CRT Scope Filters	Scope Phosphor	Approximate Brightness Loss*	Advantages	Disadvantages
Sodium yellow source with no filter. Energy emission 5900A.	Didymium filter absorbs 5900A.	P-7 P-19	60% 63%	No filter required over source.	Color coding limited. Yellow light disturbing.
Mercury light with no filter. Emission below 5900A.	Red filter which absorbs energy below 6000A.	P-7 P-19	90% 77%	No filter required over source.	Screen brightness loss great. Color coding limited.
Fluorescent with blue filter. Emission below 5400A.	Orange filter which absorbs energy below 5400A.	P-7 P-19	38% 15%	Screen brightness loss small.	Color coding limited. Blue light is unpleasant.
Any light source with a polaroid filter.	Polaroid filter oriented perpendicularly to source filter.	P-7 P-19	65% 65%	Natural lighting. Color coding unaffected.	Reflected light is depolarized. Much light control necessary.

*The screen brightness loss values are for conditions where the operators do not wear goggles with filters of the same type used over the CRT display. If such goggles are worn, the screen brightness loss is greater than the values given. The percent brightness loss for other phosphor and filter combinations can be easily determined by superimposing the filter transmission curve and the phosphor emission curve (both plotted in percent relative energy as a function of wave length) and calculating from these curves the total loss in brightness. (The phosphor emission curve should be in terms of percent relative photometric energy.)

HUMAN FACTORS IN CATHODE-RAY TUBE VISIBILITY

Adaptation

Probably the most critical single human factor in reading CRT displays is the state of adaptation of the eyes. As previously described, human eyes are extremely sensitive to changes in illumination, with pupillary adjustments occurring for small changes, and the shift from light adaptation to dark adaptation taking place over large decreases.

Under conditions of constant, or nearly steady, illumination, adaptation would not be a serious problem. However, in operational situations, the operator must shift his attention from the scope to read other instruments, to look for controls and equipment, to make settings, to write data, and often to look outside the aircraft. Following any visual change, the return to the scope often finds the operator unadapted for the scope illumination, with a consequent loss in his ability to detect targets on the scope.

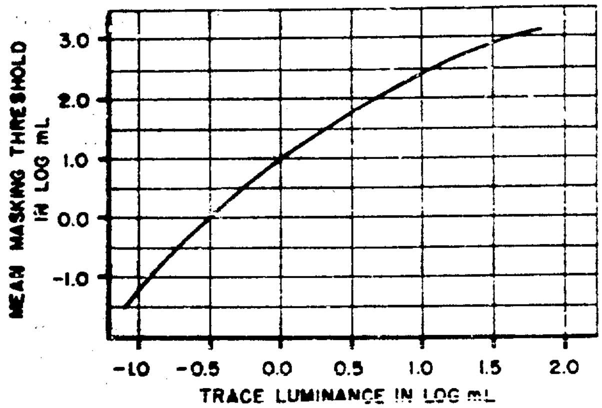


Figure 15.5 Masking Threshold Ambient Luminance Plotted Against Trace Luminance (from Adler, et al[15-3])

A common misconception, slow to be discarded, has been that surroundings must be dark for optimum scope reading[15-20]. Experiments on scope reading following adaptation to illumination levels higher than scope backgrounds have shown, as should be expected, that visibility is best when the operator is adapted to the level of the scope brightness.[15-6] However, the loss in adaptation is tolerable when the operator must do visual work at brightness levels somewhat higher than the scope level. The general recommendation is to adjust scope level so that the higher levels of illumination that must be tolerated are not more than 100 times the average scope brightness.[15-6] This rule requires an average scope brightness of at least 20 mL (1.3 log mL) if the operator must also scan daylight skies as in the case of interceptor pilots. Emphasis is added, also, to the recommendation that the operator always be permitted to adjust CRT bias to optimum brightness settings as the operational situation varies.

The recommendation that daytime interception scopes maintain an average background of 20 mL means that a strong signal will be required for visibility to provide necessary contrast. It has been determined[15-6] that with a background of 0.22 mL a contrast of 250 percent (log $\Delta B/B = 0.4$) is necessary for immediate detection of a 1200-sq min target after exposure to a brightness equivalent to daylight skies. Previous discussion of this problem (Chapter 8) pointed out that, with the decrease in required contrast with brighter background, we would not expect as high a contrast requirement at 20 mL background. Exact data are not available, but, noting in Figure 8.11, Chapter 8, that a change of background from 0.22 mL (-2.34 log mL) to 20 mL (1.3 log mL) gives a decrease from 0.5 to 1 log unit in required contrast, we can see that we would need at least 5 mL above background brightness for detectability and very likely more. The engineering problems posed by these requirements may make compromises necessary in selecting optimum scope characteristics. The principle to remember is that scopes can be read after adaptation to high brightness levels if they can be made bright enough. Figure 15.5 shows the lowest ambient illuminance required to prevent a radar signal from being detected, plotted as a function of signal luminance.

The problem is reversed under night flying conditions. Now the operator in his red-lighted cockpit is presumably dark-adapted, and our concern is with the loss of dark adaptation resulting from viewing a scope and its effect on performing other visual tasks at low levels of brightness. The general recommendation, of course, is to maintain a low level of illumination on the scope when feasible. Keeping the scope at scotopic levels, however, is out of the question, for we [illegible] Chapter 8 that cone vision is necessary for acuity (perception of details). Figure 13.17 shows visual acuity as a function of the background luminance of the acuity object at various retinal locations.

Just as red lighting for general work space has been adopted as an aid in maintaining dark adaptation, the use of red scope signals might be a possible solution to the problem when a scope must be used at night. Table 15.2 lists the hues of the phosphors most commonly used for radarscopes. While there are no true reds (675 mμ and greater), the P-19 peaks at 600 mμ, and the P-14 has a secondary emitting layer

Table 15.2 Characteristics of Phosphors Most Commonly Used for Radarscopes [15-7]

Phosphor	Peak Emission		Persistence (Time to decay to 1% max)	Contrast Ratio	Scanning Range
	Wave length (mμ)	Color			
P-7 1st stage	435	blue	a few μsec	---	
2nd stage	570	greenish-yellow	3 sec	20:1	0.1 to 5.0 scans/sec.
P-10	Scotophor	magenta trace on white background	5 sec to several months	1.2:1	0.01 to 5.00 scans/sec.
P-12	589	orange	0.5 sec	20:1	3 to 30 scans/sec.
P-14 1st stage	---	purplish-white	---	---	
2nd stage	600	orange	1 sec	20:1	0.1 to 5.0 scans/sec.
P-19	600	orange	usable persistence 30 sec	---	

peaking at 600 mμ. Referring to Figure 8.2, Chapter 8, we note that cones are near maximum sensitivity with light of 600 mμ, while rods are (relatively speaking) far less sensitive at this wave length. The P-19 phosphor (or others peaking in this region) would thus be ideal from the point of view of night operations alone. Many other factors, however, must be considered in the selection of phosphors (such as efficiency, persistence, stability, availability, and expense), and a more flexible solution to the problem is to cover the scope face with a red or amber filter. Any filter, of course, has the disadvantage of reducing signal and background brightness, requiring more power in the system. Table 15.1 contains a column labelled "Approximate Brightness Loss" that shows the effect on brightness of placing some representative filters over the scope face.

There is a report[15-13] on the effect of CRT screens on night vision which is relevant here. A cathode-ray tube was simulated at various colors and brightnesses. The test field was a white screen placed 10 feet from the subject. A circular area, 8 feet in diameter, could be illuminated at various brightness levels. The subject searched the test screen for three black discs subtending 3 degrees, 1 degree, and 0.5 degree angles at the eye. To simulate radar, cathode-ray tubes of various colors were used in standard oscilloscopes; the generated pattern approximated the A-scope of a search radar. To measure recovery time, the subject looked at the CRT screen for 30 secs and then turned to the test screen; the time to pick out silhouetted targets on the test screen was noted. The test screen was illuminated at 10 mL (like sea on dark night) and 100 mL (like clear starlit sky). Cathode-ray tube screen brightnesses were 0.2, 0.042, and 0.026 candles/ft^2. To measure the effect of glare from a CRT on the night vision of a man looking out across it, a CRT screen was placed in the subject's field of view; the increase in brightness necessary to distinguish targets on a test screen was measured. The cathode-ray tube was 16 inches from the subject and 30 degrees below the point of observation. On the average, recovery took the least time when a red CRT screen was used, only 10 percent longer with a yellow screen, but nearly twice as long with a green screen. In no case, however, was recovery time more than 30 seconds. The effect of CRT glare on night vision was least with a red tube. A yellow CRT screen at lowest brightness and a red screen at maximum brightness both decreased visual range about 10 percent. A red tube, when dim, reduced range 5 percent, while a bright green tube reduced range 40 percent.

The angle at which a scope is viewed will have some effect on detection, for extremely oblique viewing angles foreshorten and thus reduce in size the signals that are to be detected. It is advisable to mount a scope so that the plane of the scope face is perpendicular to the operator's line of sight, but viewing angles up to 30 degrees can be tolerated if necessary.[15-6]

Training in Technique

While the basic human visual capacities cannot be changed, the human being can be trained to make the most effective use of his capacities. Training efforts on airborne radar are concentrated more on identification of targets than on basic visibility. However, some attention is paid to training operators to make optimum settings of scope parameters for visibility and to develop the searching techniques best for detection. Two recommendations can be cited as examples of specific techniques amenable to training and practice.[15-5]

1. Whenever ambient lighting conditions change, set the equipment for optimum visibility by setting the CRT bias so that pips become visible with the lowest possible video gain setting.

2. In searching on a scope with a moving sweep line, fixate on the sweep or right behind it, holding each fixation from 0.5 to 1.0 sec in order to detect the weakest pips.

The inclusion of such techniques in training programs aids the operator in getting the most from his fundamental visual capacities.

In detection, the number of sightings of very faint targets depends in part on whether the operator considers it more important to risk missing real targets or to risk reporting non-existing targets. There is some evidence that, with proper instruction, subjects can be "set" to report targets at a lower confidence level than they would normally adopt, and that this lowering of criterion actually results in more correct sightings. Perhaps the training of radar operators could include instruction and practice that would result in establishing a criterion of detection yielding higher detection performance.

Annoying and Fatiguing Factors

Just as training optimizes the returns from basic visual functions, annoying and tiring factors can reduce the returns by decreasing the probability that a weak signal will be detected. The cumulative effect of tension, boredom, danger, long periods without rest, and the like, referred to broadly as "fatigue," is a decrement in the efficiency and accuracy of performance of almost any kind of task. Certain scope factors can add to this over-all effect and should be avoided when possible. Among the more important scope factors are:

1. Poor CRT and bias settings, necessitating frequent light-dark or dark-light adaptation.

2. The annoying "flash" of blue-white light each time the sweep line crosses a target on a scope with a P-7 phosphor.

3. The eye movements required in following the rotating sweep line on a PPI scope.

4. The necessity for a large amount of accommodation and convergence when space requirements force short viewing distances.

5. The effort used in trying vainly to bring to clear focus the blurred images resulting from limitations in scope resolution.

Precise evaluation of the effects of these factors has not been made. It is recommended, however, that they be avoided when possible by incorporating in the design of systems adequate control of bias and gain, control of ambient illumination through filter and screening, adequate viewing distances, reasonable work periods, and the like.

INTERCEPTION

In instrument flight, air-to-air visibility problems resolve themselves [illegible] which occur during an interception mission. Interception on instruments introduces nothing basically new in visual problems. However, each type of mission does present visual problems more or less typical of the mission, where particular visual factors assume special importance and where particular interactions of factors become critical.

The instrumentation that is specific to interception falls almost exclusively into the category of instruments using cathode-ray tube displays. The visual problems specific to instrument interception then reduce to problems of reading and reacting to information displayed on cathode-ray tubes.

In an interception mission, the pilot (or the observer in two-place interceptors) must first locate a target on his scope. He is generally directed to the vicinity of the target by a ground control unit, and thus knows about when and where to expect his target to appear. However, the pilot or observer must first detect and then identify the target return. Having located a target on the scope, the general procedure is then to set an indicator on the target by manipulation of hand controls (lock-on) and then to fly the aircraft in such a way that errors presented on the scope are nullified. Both of these functions involve the kind of eye-hand coordination tasks generally labelled as "tracking" Details of data presentation and operator response vary from aircraft to aircraft, but all types of instrument interception practiced today and contemplated for the near future can be described in terms of identification and tracking.

In regard to problems of interception, the operator might be aided in his search phase by the addition of equipment that eliminates everything from the scope that is not moving (MTI), by adding a signal given off by friendly aircraft (IFF), or by coding critical returns electronically. In a sense, this last aid is provided by means of the symbolic displays produced in feeding signals through a computer before bringing data to the scope in attack phases of interception. Regarding the coding of signals in general, it is possible to use any of a number of modes as a code dimension. For example, there has been some experimentation[15-13] with color coding of signals as an aid in reducing confusion (the operator flying the red ring to the red dot and ignoring signals of any other color, for instance). Color coding, of course, introduces all the problems of color vision discussed previously (e.g., Chapter 8), and these basic characteristics must be taken into account in a color coding system. Of particular importance is the effect of ambient illumination on colors; color coding in a red-lighted cockpit would be difficult and, at best, very restricted in number of code steps (discriminable colors) that could be used. Table 15.3 summarizes the major visual coding methods[15-6] that might be incorporated in airborne systems.

Some preliminary investigation[15-2] has been made of sounding a warning bell or buzzer when a new target is picked up by the system, or when the sweep line passes over a friendly target (IFF). Early results suggest that such auditory coding is feasible.

The use of MTI, IFF, or various coding signals generally requires too much auxiliary equipment for airborne use today, but developments along these lines can lead to improved identification in the future, and some systems are now in use.

Considerable work has been done in evaluating various aids for precisely locating points in radar displays. Under various circumstances, overlays with grids or other information, cursors, strobes, aiming dots and rings, and the like, have proven effective. Many of these aids have been devised primarily to help determine azimuth, bearing, and altitude readings and typically do not apply to interception problems.

Table 15.3 Summary Table of Coding Methods[15-6]

Code Dimension	Number of Code Steps	Evaluation	Comments
Color	11	good	Objects of a given color quickly and easily identified in a field of various colored objects. Little space required.
Numerals and letters	unlimited	good	Number of coding steps unlimited. Requires little space if there is good contrast and resolution.

Table 15.3 Summary Table of Coding Methods[15-6] (cont)

Code Dimension	Number of Code Steps	Evaluation	Comments
Geometric figures	15 or more	good	Certain geometric shapes are easily recognized. Little space required, if resolution is good.
Arc	5	fair	Requires considerable space on display.
Visual number	6	fair	Requires considerable space on display.
Length	4-5	fair	Limited number of usable code steps. Will clutter a display with many signals.
Angular orientation	12	fair	95% of the estimates will be in error by less than 15°.
Brightness	3-4	poor	Limited number of usable code steps. Poor contrast effects will reduce visibility of weaker signals. Fatiguing.
Flash rates	5	poor	Distracting and fatiguing. Interacts poorly with other codes.
Stereoscopic depth	?	fair	Realistic method of coding range or altitude. Requires complex electronic displays.

The typical presentation for interception is a symbolic display consisting of a small circle (the operator's aircraft) to be kept centered on a moving dot (the target) with a single range ring to represent target distance. The position of a break in the range ring (read as position on a clock face) gives rate of closure. A straight line represents the horizon. There appears to be little literature of an experimental nature comparing such aids with other possible types for effectiveness. The little literature available is concerned with tracking more than with identification.

Most of the literature on tracking does not apply directly to problems of interception, because the classical laboratory studies have been done in vastly simpler circumstances than prevail in airborne combat operations. Much work has been done on direct tracking, where a moving element of a display duplicates exactly the directional movement of a control with a constant ratio of display-control movement magnitude. This simple kind of tracking is encountered operationally only in the lock-on phase of some interception procedures, where the follower spot or cross-hair is moved onto the target by manipulation of a joy-stick type control. Experimental investigation of direct tracking with a joy-stick has shown the procedure to be speedy and accurate.[15-14]

Some interest has been shown in comparing various types of control devices for their relative effects on the speed and accuracy of tracking.[15-7] The aforementioned joy-stick has been compared with the rolling-ball control. When small setting movements were necessary, both controls were equally fast, but the joy-stick proved to be the speedier control for longer control movements. A free-moving, hand-held stylus that is moved like a pencil across an electrically conducting glass plate has been shown to be faster than the joy-stick, although no more accurate. Other types of controls that have been used include handwheels or cranks, and a light gun (a pistol-like variant of the free-moving stylus). No one type of control can be recommended as superior under all conditions. However, if other factors dictate a particular type of control, reasonably satisfactory human performance may be expected from any of the above types.

Most of the tracking in combat operations falls into the category of aided tracking, where the display responds to control movement in direction, but with a velocity component added that permits relatively extensive display movements in response to small control movements. Even this situation grossly oversimplifies the situation in flight operations, because the display movement is the result of the complex maneuvering of the whole airplane in response to many other factors beside the stick motion. So the studies of aiding time constants and the like are not applicable here.

The most relevant area of experimental literature is that concerned with "fly-to" vs. "fly-from" types of display-control relations. This area is discussed in the chapter on instrumentation. The general consensus of the studies is that "fly-from" displays are more "natural" than the "fly-to," are learned more readily, and produce fewer errors.[15-6] There is evidence that transfer from "fly-from" to "fly-to" is difficult, but transfer is good from "fly-to" to "fly-from," suggesting that re-education from conventional "fly-to" instruments in use today would not be as serious a problem as some would make it.[15-19] The practice of abruptly changing from one type of display to another in the last few seconds of an interception attack is considered undesirable in an evaluation of human factors in interception.[15-11]

BOMBARDMENT

In the instrument bombing situation, many factors differ from the interception problem, especially with regard to the fact that we are dealing with a stationary rather than a moving target. However, in the final analysis, the bombardier's two major functions are identification and tracking. Identification of target or aiming point is more difficult, generally, then in interception, while tracking is relatively simpler with the stationary target, but the functions remain the same; only the emphasis differs.

Just barely seeing a signal on a radarscope is generally not enough in bombardment. The operator must recognize what is seen and react to it properly. Thus, the problem of target identification warrants consideration.

Identification involves interpretation from a heterogeneous collection of areas with different brightnesses. Psychologists have named this process of interpretation "perception," and a great amount of experimental work has been done in the area of visual perception. It seems that the essence of visual perception consists in breaking up the gross mass of stimuli with which one is continually bombarded into clusters, groups, or patterns of stimuli which have meaning of some kind through past experience with similar patterns. Thus, we may be stimulated by stimuli describable as different kinds and shapes of blue, white, green, light, dark, etc., but, because these stimuli form a familiar pattern, we perceive a tree against a cloudy sky.

In the case of interpretation of radar displays, the characteristics determining the patterns most crucial for identification purposes are form characteristics. The following discussion is concerned with factors affecting the operator's ability to distinguish and identify forms in the scope presentation.

Of course, most of the factors that affect visibility of signals also operate in affecting form perception. What has been said previously regarding contrast between signal and background as a function of CRT bias, signal gain, and the other equipment parameters, as well as such human factors as adaptation, training, and fatigue, holds with regard to identification. There are, however, additional factors in identification that can be controlled to some extent in equipment design or in training.

First, let us consider some relevant characteristics of human form perception. Everything else being equal, there is a general tendency for larger forms to be more easily recognized than smaller forms.[15-12, 15-15] Shape, of course, plays an important part in form recognition. That is, some shapes are more easily recognized than others, and similar shapes are more likely to be confused than are different shapes.[15-9]

One study[15-15] of shape recogni[illegible] on PPI-scopes found that the shapes studied ranked as follows from "easy" to "hard" to dis[illegible]ate: triangle, circle, trapezoid, square, rectangle, and ellipse. Those most frequently c[illegible]d were: circle and ellipse, square and rectangle,

and triangle and trapezoid. With more complex shapes, those symmetrical about a vertical axis (upright figures) are more easily recognized than those symmetrical about a horizontal axis (lying down).[15-9] Another important determiner of form recognition is its familiarity. We can recognize a number or a letter under conditions where less familiar forms might not be recognized.[15-12]

The factors above were mentioned as if one's task were simply to look at a single figure and tell whether or not he can identify it. Generally, a scope operator's task is more complex, involving the recognition of a particular form in a display containing a variety of forms. Specifically, in the case of the bombardier, the task is to identify certain forms (orientation points, aiming points, target areas, etc.) that he expects to see, differentiating them from surrounding forms. The factors given above (size, shape, familiarity) operate also to help pick out a desired form from a mixed field of forms, but they are not always of primary importance in operational situations.

In predicting what form will stand out most clearly from its background, the difference between the form to be identified and the surrounding forms is of primary importance. We have already noted the tendency for similar forms to be confused with one another. So it is readily apparent that, although a triangle is more accurately identified than an ellipse when either appears in a fairly uncluttered field, an ellipse would stand out better than a triangle in a field filled with triangles. The uniqueness of a form, then, is important in determining how readily it can be identified. Shape and size both contribute to this uniqueness. So, the selection of aiming points consisting of or associated with unique returns on a radar scope will increase the probability of correct identification on a mission.

Noise or clutter in a background will reduce contrast and obscure the contours of forms to be identified. Identification gets worse, the more confusing forms there are in the field, and the less time there is to locate the desired form.[15-8] Although experimental evidence is sparse, it is reasonable to predict that forms resembling the forms encountered in noise and clutter patterns will be more seriously masked than forms not resembling the clutter.[15-2] Thus, it would be unwise to depend on identifying an aiming point in an area whose returns closely resembled typical cloud returns.

It is misleading, however, to consider the aiming-point problem simply in terms of picking out a single form from a heterogeneous field. Actually, the whole field is a pattern, and when critical elements of the pattern can be identified, they can be used as secondary cues leading to the aiming point. That is, many unique returns on a scope, of known bearing and distance from the aiming point, may be utilized as orientation points to aid in locating the aiming point and in verifying the point chosen as the correct one. These secondary cues, then, serve as integrating factors rather than as distracting, confusing, or disintegrating factors, and the probability of correct identification is increased if the details of the over-all pattern are studied and interpreted.

The scope pattern on a bombing mission is continually changing. As the target area is approached, it will first be identified by a gross pattern, with many unique areas serving to locate the more localized target area. As the target is approached, its surrounding area expands on the scope and the gross return breaks down into finer returns, permitting increasing precision in the location of the aiming point. So there is a continual change in the forms to be recognized and a continual breakdown of the pattern being interpreted. Here the principle of familiarity assumes importance; the more forms the operator can anticipate, and the more thoroughly he has studied predicted returns, then the more familiar the patterns will be as they develop, and the more readily the critical elements will be located. A study[15-10] of errors in identifying aiming points has clearly demonstrated the importance of stressing target patterns and optimum equipment settings during mission planning and of utilizing secondary cues in all phases of a bombing mission.

With this information, what can we say about the design of radar systems with regard to maximizing the speed and accuracy of identification? First, the sharpness of resolution of the system is important. Many studies[15-12] have shown that identification of forms improves with the sharpness of the contours. Since current equipment does not yet approach the degree of resolution possible with the eye, equipment improvement may be expected to result in improvement in identification. Anything that will improve the faithfulness with which the various system components reproduce signal changes should result in sharper images. Increasing the sensi-

tivity of lobe patterns through refinements in transmitter systems and antennas should lead to improvement in identification.

A study[15-18] of transition zones between areas of different brightness on scope faces has emphasized the importance of brightness gradients between areas in determining the detectability of the brightness difference. Apparently the human observer can reform and sharpen the gradient of light separating a return from the background illumination on a radar screen,[15-16] and visual resolution may improve on the equipment resolution. This study suggests that, after a certain point, decreasing the gradient of brightness between a return and background may be less effective in improving visual resolution than electronically "sharpening" or "emphasizing" discontinuities in the gradient. These findings may account for the fact that aiming-point identification improves with increasing scope size even though scope resolution remains unchanged. A study[15-11] of the problem of target identification in radar bombing has shown that aiming-point settings are consistently more accurate on 12-inch than on 5-inch scopes. When space occupied by the equipment is a critical factor, a 7- or 8-inch scope should be a satisfactory compromise. When larger scopes are permissible, however, they would be desirable. This line of development will require considerable future study before specific recommendations are possible.

Identification is frequently aided when the operator can turn down his gain so that irrelevant weak background returns, and noise, disappear from the scope, leaving fewer signals to discriminate among. This technique demonstrates the importance of predetermining what features in an area will give strong returns, and it emphasizes once again the need for permitting the operator some freedom in adjusting gain.

At the time of writing, the typical aid for bombing location is a single azimuth radius and a single range ring whose intersection forms a pair of cross-hairs to be centered in the aiming point. In bombing, however, the operator must take his display as he finds it, and the major activity he can undertake that will pay off in improved identification is his preparation for a mission. Great importance must be attached to the prediction of what the radar picture will be like. Radar reconnaissance photographs of the target area are of prime value. Without this information, however, it is possible to deduce roughly from maps, aerial photographs, and other intelligence what the radar return characteristics should be. Remembering the importance of uniqueness, familiarity, and target patterning, we can recommend the following procedures as vital to accurate target or aiming point identification:

1. Using all information available, determine beforehand what the radar picture will be at various points on the approach and on the bomb run.

2. Select an aiming point in terms of ease of identification.

   a. A point giving a unique return with respect to its surroundings at close range

   b. A point that will be part of a larger unique return at longer ranges

3. Determine a number of secondary cues -- unique patterns at known range and azimuth from the aiming point.

4. Become familiar with the gross and fine patterns of the mission by thorough study.

   a. Learn the unique forms the target area and aiming point will assume at various ranges.

   b. Learn the unique forms of the secondary cues.

   c. Learn the pattern formed by the aiming point and the secondary cues in combination.

   d. Study these patterns and forms as they are likely to appear from various axes of attack. (Rotation of a form can decrease the ease of identification[15-4]. Remember also that the radar returns from a given object are different in different directions.)

Application of these rules should minimize errors in aiming-point identification by minimizing the disruptive effects of noise, weather, clutter, ECM, and the like, although there is no remedy for a badly obliterated picture.

Training is extremely important with regard to target recognition, since identification is so much a developed skill rather than an inborn capacity. With regard to the visual problems of identification, training should stress:

1. The techniques listed above for minimizing failure to identify targets or aiming points

2. Techniques of equipment adjustment for presentation minimizing noise and clutter

LIST OF REFERENCES

15-1 Anon. Handbook of Human Engineering Data for Design Engineers. Tech. Report No. SDC 199-1-2a. Office of Naval Research, Special Devices Center, Port Washington, N.Y. 1952.

15-2 Anon. Second Annual Report on Perception of Forms in Electro-Visual Display Systems. Contract DA 49-007-MD-[illegible]. Tufts University, Medford, Mass. November 1954-October 1955.

15-3 Adler, H. E., Kuhns, M. P., and Brown, J. L., Masking of Cathode Ray Tube Displays by Ambient Illumination. WADC Tech. Report 53-[illegible]. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. November 1953.

15-4 Arnoult, M. D., "Shape Discrimination as a Function of the Angular Orientation of the Stimuli." J. Exp. Psychol. Vol. 47. 1954. pp. 323-328.

15-5 Baker, P., Kappauf, W. E., and Payne, M. C., Review of Psychological Research Bearing on Radar-scope Interpretation in ADC Operations. Tech. Report 53-[illegible]. HRRC, Lackland Air Force Base, San Antonio, Texas.

15-6 Baker, C. A., and Grether, W. F., Visual Presentation of Information. WADC Tech. Report 54-160. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. August 1954.

15-7 Baker, C. H., and Thornton, C. B., Canada. DRHL Report No. 84. December 1953

15-8 Boynton, R. M., and Bush, W. R., Laboratory Studies Pertaining to Visual Air Reconnaissance. WADC Tech. Report [illegible]. Part [illegible]. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. September 1953.

15-9 Casperson, R. C., "The Visual Discrimination of Geometric Forms." J. Exp. Psychol. Vol. 40. 1950. pp. 668-681.

15-10 Daniel, R. S., and Eason, R. G., Tech. Report TR-54-3. AFPTRC, Lackland Air Force Base, San Antonio, Texas. April 1954. (CONFIDENTIAL)

15-11 Dubrowner, H. J., and Ayre, T. P., Tech. Report 53-29. HRRC. Lackland Air Force Base, San Antonio, Texas. September 1953. (CONFIDENTIAL)

15-12 Fox, Wyatt R., Visual Discrimination as a Function of Stimulus Size, Shape and Edge-Gradient, Unpublished Doctor's Dissertation, Boston University 1954 (Abstract).

15-13 Gebhard, J. W., Tech. Report No. SDC 166-1-126. Office of Naval Research, Special Devices Center, Port Washington, N. Y. July 1, 1951. (CONFIDENTIAL)

15-14 Gebhard, J. W., Tech. Report No. SDC 166-1-118. Office of Naval Research, Special Devices Center, Port Washington, N. Y. November 1950.

15-15 Gerathewohl, S. J., and Rubinstein, D., Investigation of Perceptual Factors Involved in the Interpretation of PPI-Scope Presentations. II. A Pilot Study on Form Discrimination. USAF School of Aviation Medicine, Randolph Field, Texas. Vol. 8. p. 27.

15-16 Hake, H. W., and Averbach, E., Apparent and Real Resolution in Radar Visibility. WADC Tech. Report 55-459. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.

15-17 Morgan, C. T., Theory and Problems of Radar Visibility, Intensity Modulated Scopes. NRL Report 3065. JHU Report 166-I-148. Naval Research Lab., Washington, D. C. April 1948.

LIST OF REFERENCES (Cont)

15-18 Tousey, R., Report on Effect of CRT Screens on Night Vision.

15-19 Weiss, F., Magnifiers Enlarge the Pip.

15-20 White, C. T., Polarized-Light Illumination of Radar and Sonar Spaces and Comparison with Limited Spectrum Methods. Report No. 6[illegible]. U. S. Navy Electronics Lab., San Diego, Calif. 1950. p. 112.

15-21 Williams, S. B., "Visibility on Radar Scopes." Chapter 4 in Human Factors in Undersea Warfare. U. S. National Research Council, Washington, D. C. 1949.

15-22 Woodson, W. E., Human Engineering Guide for Equipment Designers. University of California Press, Berkeley, Calif. 1954.

GENERAL BIBLIOGRAPHY

15-23 Anon. "Cockpit View vs. Screen Image." Aviation Week. Vol. 54, No. 20. 1951.

15-24 Anon. Notes on Oblique-Angle Viewing of Radar and Other Displays. [illegible] February 1954.

15-25 Anon. Principles of [illegible] VII. Additional Properties of the Eye. Report No. 7142. Hazeltine Corp. April 27, 1953.

15-26 Anon. Standards to be Employed in Research on Visual Displays. Armed Forces National Research [illegible] Committee, Ann Arbor, Mich. March 1950.

15-27 Anon. Report to the Services No. 102. (Foxboro Co. Report on Studies in Aided Tracking attached). U. S. Office of Scientific Research and Development, National Defense Research Committee, Div. 7. October 1945.

15-28 Anon. Report to the Services No. 79. U. S. Office of Scientific Research and Development, National Defense Research Committee. (Foxboro Co. Report attached) April 1945. CONFIDENTIAL

15-29 Adair, E. R., "Duration and Light-Dark Ratio of Intermittent Pre-adaptation as Factors Influencing Human Dark Adaptation." J. Opt. Soc. Amer. Vol. 43. January 1953. pp. 22-27.

15-30 Adams, J. K., Gray, F., and Knauft, E. B., An Experimental Determination of Variable Errors in Ranging on a Surface Target by Radars Marks 4, 8, and 10. Report No. 17. University of Wisconsin, U. S. Office of Emergency Management. February 13, 1945.

15-31 Allen, L. K., and Dallenbach, K. M., "The Effect of Light-Flashes during the Course of Dark Adaptation." Amer. J. Psychol. Vol. 51. July 1938. pp. 540-548.

15-32 Baach, A. M., Haggard, D. F., Seiden, R., Vineberg, R., and Wischner, G. J., A Bibliography of Human Factors in Radar Operation and Maintenance. HRRO, The Dept. of the Army. September 1953.

15-33 Bartlett, Sir Frederic, Radar Display Research at the RAF Radar Research Unit. Great Britain. Report No. 801. Flying Personnel Research Committee. August 1952.

15-34 Bartlett, N. R., Williams, S. B., and Hanes, R. M. "Visibility on Cathode-Ray Tube Screens. The Effect of Size and Shape of Pip." J. Opt. Soc. Amer. Vol. 39. June 1949. pp. 463-470.

15-35 Beier, D. C., and Taylor, R. A. Project N-114. Report No. 30. University of Wisconsin, U. S. Office of Emergency Management. April 16, 1945.

15-36 Bowen, H. M., Signal Visibility on a B-Scan Radar Display: A Study of Noise Brightness and Noise Pattern. FPRC 782. Flying Personnel Research Committee, Royal Air Force Radar Research Unit, Psychological Lab., Cambridge, England. February 1952.

15-37 Brantley, J. Q., Jr., A Study of the Aircraft Collision Problem with Particular Emphasis on the Possible Application of Continuous Wave Radar Techniques and Appendix. Report No. JA-774-P-1. Cornell Aeronautical Lab., Inc., Buffalo, N. Y. September 1952.

15-38 Brogden, W. J., OSRD No. 5358. U. S. Office of Scientific Research and Development, National Defense Research Committee. July 23, 1945.

15-39 Brown, J. L., "Effect of Different Pre-adapting Luminances on the Resolution of Visual Detail during Dark Adaptation." J. Opt. Soc. Amer. Vol. 44. No. 1. January 1954. pp. 48-55.

15-40 Brown, John L., Diamond, Leonard, and Adler, Helmut E., "The Effect of Duration of Light Adaptation on Time Required for Detection of a Target on a Simulated PPI Scope." J. Opt. Soc. Amer. Vol. 43. No. 12. December 1953. pp. 1147-1152.

15-41 Brown, W. R. J., and MacAdam, D. L., "Visual Sensitivities to Combined Chromaticity and Luminance Differences." J. Opt. Soc. Amer. Vol. 39. October 1949. pp. 808-834.

15-42 Browne, R. C., Figure and Ground in a Two-Dimensional Display. FPRC 791. Flying Personnel Research Committee. (University of Durham). July 19 2.

15-43 Buckley, Barbara B., Hanes, R. M., and Deese, J., Search Area and Target Detectability on a PPI Cathode-Ray Tube. WADC Tech. Report No. 52-303. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. April 1953.

15-44 Burnham, Robert W., "Comparative Effects of Area and Luminance on Color." Amer. J. Psychol. Vol. 65. January 1952. pp. 23-78.

15-45 Burnham, Robert W., "The Dependence of Color upon Area." Amer. J. Psychol. Vol. 64. October 1951. pp. 521-533.

15-46 Canfield, A. A., Comrey, A. L., and Wilson, R. C., "A Study of Reaction Time to Light and Sound as Related to Increased Positive Radial Acceleration." J. Aviat. Med. Vol. 20. No. 5. 1949. pp. 350-355.

15-47 Chapanis, A., The Relative Efficiency of a Bearing Counter and Bearing Dial for Use with PPI Presentations. Memo Report. Office of Naval Research, Special Devices Center, Johns Hopkins University, Systems Research Field Lab. August 1947.

15-48 Chapanis, A., Tech. Report No. SDC 166-I-3. Office of Naval Research, Special Devices Center, Port Washington, N. Y. November 1, 1946.

15-49 Cheatham, P. G., and White, C. T., "Temporal Numerosity: I. Perceived Number as a Function of Flash Number and Rate." J. Exp. Psychol. Vol. 44. 1952. pp. 447-451.

15-50 Cheatham, P. G., and White, C. T., "Temporal Numerosity: III. Auditory Perception of Number." J. Exp. Psychol. Vol. 47. 1954. pp. 425-428.

15-51 Coakley, J. D., Fucigna, J. T., and Barmack, J. E., A Functional Application of Anthropometric Data to the Design of the Work Space of PPI Scope Operators. WADC Tech. Report 53-3. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. January 1953.

15-52 Coleman, Howard S., and Harding, Samuel W., Notes on the Scattering of Light in Optical Fire Control Instruments. Report 144. U. S. Office of Scientific Research and Development, National Defense Research Committee. October 19, 1945.

15-53 Coleman, P. D., and Krauskopf, J., The Influence of High Intensity Noise on Visual Thresholds. AMRL Project 6-95-20-001. Report No. 222. Army Medical Research Lab., Research and Development Div., Fort Knox, Ky. February 1956.

15-54 Cooper, F. S., Liberman, A. M., and Borst, J. M., "The Interconversion of Audible and Visible Patterns as a Basis for Research in the Perception of Speech." Proc. Nat. Acad. Sci. Vol. 37. 1951. pp. 318-325.

15-55 Craik, K. J. W., and MacPherson, S. J., The Effect of Certain Operating Conditions on the Visibility of PPI Radar Echoes. Great Britain. A.P.U. 16. Medical Research Council, Applied Psychology Research Unit. MRC 48/25. Psychological Lab., Cambridge, England. November 1945.

15-56 Day, W. F., and Beach, B. R., A Survey of the Research Literature Comparing the Visual and Auditory Presentation of Information. WADC Tech. Report No. 5021. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. November 1950.

15-57 Dempster, W. T., Space Requirements of the Seated Operator. Geometrical, Kinematic, and Mechanical Aspects of the Body with Special Reference to the Limbs. WADC Project 7214. Tech. Report No. 55-159. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. July 1955.

15-58 Ellis, W. H. B., Burrows, A., and Jackson, K. F., with Statistical Analysis by D. G. C. Gronow. Great Britain. Report No. 841. Flying Personnel Research Committee. August 1953. (CONFIDENTIAL)

15-59 Evans, Ralph M., "Psychological Aspects of Color and Illumination." Illum. Engng. Vol. 46. April 1951. pp. 176-181.

15-60 Farnsworth, Dean, The Effect of Colored Lenses upon Color Discrimination. Report No. 73. Medical Research Lab. Color Vision Report No. 9. U. S. Naval Submarine Base, New London, Conn. September 3, 1945.

15-61 Farnsworth, Dean, and Hillman, Beverly, A Comparison of Specifications for Dark Adaptation Red. Report No. 4. Vol. 12. Medical Research Lab. Report No. 219. U. S. Naval Submarine Base, New London, Conn. February 2, 1953.

15-62 Ford, A., and Getz, M. H., The Perceptive Illusion in Radar Sector Scopes. USAF Tech. Report 1. United States Air Force, Air Materiel Command, Watson Lab., Red Bank, N. J. June 1948.

15-63 Fraser, D. C., The Speed and Accuracy of Plotting with a Simulated PPI Marker Strobe. Part II. The Relation of Speed to Accuracy. Great Britain A.P.U. 128/50. Medical Research Council, Applied Psychology Research Unit, Psychological Lab., Cambridge, England. March 1950.

15-64 Fry, G. A., Effect of Chromatic Adaptation upon Normal Color Vision. ONR Project NR 140-061. RF Project 537. Final Report. Phase 3. Office of Naval Research, Ohio State University, Research Foundation. March 1954.

15-65 Fry, G. A., and Ward, H. O., Effect of Chromatic Adaptation upon Normal Color Vision. ONR Project NR 140-061. RF Project 537. Final Report. Phase 2. Office of Naval Research, Ohio State University Research Foundation. March 1954.

15-66 Garner, W. R., Some Perceptual Problems in the Use of the VG Remote PPI. Tech. Report (SDC No. 166-I-2. Office of Naval Research, Special Devices Center, Port Washington, N. Y. September 15, 1946.

15-67 Garner, W. R., A Study of Factors Affecting Operation of the VG Remote PPI. Tech. Report No. SDC 166-I-1. Office of Naval Research, Special Devices Center, Port Washington, N. Y. August 1946.

15-68 Garner, W. R., Hanes, R. M., and Reed, J. D., Calculation of Bearing and Range Errors Due to Delays in Transmission of Radar Information. Tech. Report No. SDC 166-I-11. Office of Naval Research, Special Devices Center, Port Washington, N. Y. February 1947.

15-69 Garner, W. R., Saltzman, Dorothy C., and Saltzman, I. J., Tech. Report No. SDC 166-I-95. Office of Naval Research, Special Devices Center, Port Washington, N. Y. August 10, 1949.

15-70 Gebhard, J. W., Psychological Problems in Coding the Information for Visual Displays. Tech. Report No. SDC 166-I-93. Office of Naval Research, Special Devices Center, Port Washington, N. Y. May 1949.

15-71 Gebhard, J. W., Tech. Report No. SDC 166-I-101. Office of Naval Research, Special Devices Center, Port Washington, N. Y. February 10, 1947.

15-72 Gebhard, J. W., Barber, J. L., and Halsey, R. M., Tech. Report No. SDC 166-I-81. Office of Naval Research, Special Devices Center, Port Washington, N. Y. May 1, 1949.

15-73 Gebhard, J. W., and Bilodeau, E. A., Tech. Report No. SDC 166-I-37. Office of Naval Research, Special Devices Center, Port Washington, N. Y. December 15, 1947.

15-74 Gebhard, J. W., and Mowbray, G. H., Effect of the Reflection Plotter on the Visibility of Signals on PPI Screens. Tech. Report No. SDC 166-I-119. Office of Naval Research, Special Devices Center, Port Washington, N. Y. December 1950.

15-75 Gerathewohl, S. J., "Brightness Contrast and Target Identification Thresholds on the Radar PPI." J. Aviat. Med. Vol. 26. October 1955. pp. 399-408.

15-76 Gerathewohl, S. J., Investigation of Perceptual Factors Involved in the Interpretation of PPI-Scope Presentation. Form Discrimination under Conditions of Heavy Video-Noise. Project 21-1205-0004. Report No. 1. USAF School of Aviation Medicine, Randolph Field, Texas. July 1953.

15-77 Gerathewohl, S. J., "Eye Movements during Radar Operations." J. Aviat. Med. Vol. 23. 1952. pp. 597-607.

15-78 Gerathewohl, S. J., Investigation of Perceptual Factors Involved in the Interpretation of PPI Scope Presentations. USAF Project 21-24-009. Report No. 1. School of Aviation Medicine, Randolph Field, Texas. September 1950.

15-79 Gerathewohl, S. J., and Taylor, W. F., "Effect of Intermittent Light on the Readability of Printed Matter under Conditions of Decreasing Contrast." J. Exp. Psychol. Vol. 46. 1953. pp. 278-282.

15-80 Gray, Robert C., "Individual Differences in Colour Vision." Brit. Med. Bull. Vol. 9. No. 1. 1953. pp. 79-81.

15-81 Green, B. F., McGill, W. J., and Jenkins, H. M., The Time Required to Search for Numbers on Large Visual Displays. Tech. Report No. 36. Massachusetts Institute of Technology, Lincoln Lab., Bedford, Mass. August 1953.

GENERAL BIBLIOGRAPHY (Cont)

15-82 Griffin, D. R., Hubbard, R., and Wald, G., "The Sensitivity of the Human Eye to Infra-Red Radiation." J. Opt. Soc. Amer. Vol. 37. 1947. pp. 546-554.

15-83 Guth, Sylvester, K., and Eastman, Arthur A., "Brightness Difference in Seeing." Amer. J. Optom. Vol. 31. 1954. pp. 567-577.

15-84 Guth, Sylvester, K., Comfortable Brightness Relationships for Critical and Casual Seeing. Preprint No. 30. National Technical Conference of Illuminating Engineering Society, Pasadena, Calif. August 1950.

15-85 Hanes, R. M., and Williams, S. B., "Visibility on Cathode-Ray Tube Screens: The Effects of Light Adaptation." J. Opt. Soc. Amer. Vol. 38. April 1948. pp. 363-377.

15-86 Harriman, M. W., "Visibility of Cathode-Ray Tube Screens: Search Time as a Function of Signal Strength." J. Psychol. Vol. 29. 1950. pp. 247-250.

15-87 Harriman, M. W., and Williams, S. B., "Visibility on Cathode-Ray Tube Screens: Positive Vs. Negative Signals on an Intensity Modulated Scope." J. Opt. Soc. Amer. Vol. 40. February 1950. pp. 102-104.

15-88 Hartridge, H., "Recent Advances in Color Vision." Science. Vol. 108. October 15, 1948. pp. 395-404.

15-89 Helson, Harry, "Multiple-Variable Analysis of Factors Affecting Lightness and Saturation." Amer. J. Psychol. Vol. 55. No. 1. January 1942. pp. [illegible]-57.

15-90 Helson, Harry, "Color Tolerances as Affected by Changes in Composition and Intensity of Illumination and Reflectance of Background." Amer. J. Psychol. Vol. 52. July 1939. pp. 406-412.

15-91 Helson, Harry, "Fundamental Problems in Color Vision. I. The Principle Governing Changes in Hue, Saturation, and Lightness of Non-Selective Samples in Chromatic Illumination." J. Exp. Psychol. Vol. 23. No. 5. November 1938. pp. 439-476.

15-92 Helson, Harry, and Jeffers, Virginia Balough, "Fundamental Problems in Color Vision. II. Hue, Lightness, and Saturation of Selective Samples in Chromatic Illumination." J. Exp. Psychol. Vol. 26. No. 1. January 1940. pp. 1-27.

15-93 Helson, H., and Michels, W. C., "The Effect of Chromatic Adaptation on Achromaticity." J. Opt. Soc. Amer. Vol. 38. 1948. pp. 1025-1032.

15-94 Henneman, R. H., and Long, E. R., A Comparison of the Visual and Auditory Senses as Channels for Data Presentation. WADC Tech. Report 54-363. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. August 1954.

15-95 Herrick, R. M., Diamond, A. L., and Kuhns, Margaret P., Luminance Thresholds during Dark Adaptation Following Pre-adaptation to Cathode Ray Tube Displays. WADC Tech. Report 52-260. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. December 1952.

15-96 Humphrey, C. E., Auditory Displays. I. Spatial Orientation by Means of Auditory Signals. An Exploratory Study. Applied Physics Lab., Johns Hopkins University, Silver Spring, Md. January 1952.

15-97 Humphrey, C. E., and Thompson, J. E., Auditory Displays. II. Comparison of Auditory Tracking with Visual Tracking in One Dimension. Project 20-F-1. Applied Physics Lab., Johns Hopkins University, Silver Spring, Md. April 1953.

15-98 Jameson, Dorothea, and Hurvich, Leo M., "Spectral Sensitivity of the Fovea. II. Dependence on Chromatic Adaptation." J. Opt. Soc. Amer. Vol. 43. July 1953. pp. 552-559.

15-99 Jenness, A. F., and Rouse, R. O., Operator Capacity to Predict Target Position. Project Report No. 1. Williams College, Williamstown, Mass. September 1953.

15-100 Levine, D., Significance of Line Width in PPI Displays. Report No. GER-6142. Goodyear Aircraft Corp., Akron, Ohio. June 1954.

15-101 Leyzorek, M., Tech. Report No. SDC 166-I-41. Office of Naval Research, Special Devices Center, Port Washington, N. Y. February 10, 1948.

15-102 Lichte, W. H., Steinschneider, A., Eason, R. G., and Daniel, R. S., Effectiveness of Configuration Target Study on Radar Aiming Point Identification. Project 7711. Task 77202. Tech. Memo AORL-TM-55-1. AFPTRC, Air Research and Development Command, Mather Air Force Base, Calif. February 1955.

15-103 Lindsley, D. B., Final Report in Summary of Work on the Selection and Training of Radar Operators. OSRD No. 5766. Research Report No. 19. U. S. Office of Scientific Research and Development, National Defense Research Committee, Applied Psychology Panel, Yerkes Lab. of Primate Biology, Orange Park, Fla. September 24, 1945.

15-104 Lindsley, D. B., et al., A Radar Trainer and Flash-Reading Method for Operators of the Plan Position Indicator. Project SC-70. OSRD No. 4489. Research Report No. 14. U. S. Office of Scientific Research and Development, National Defense Research Committee, Applied Psychology Panel, Yerkes Lab. of Primate Biology, Orange Park, Fla. December 1944.

15-105 Lindsley, D. B., Anderson, I. H., Baldwin, A. L., et al, Factors Determining Accuracy of Reception of Oscilloscope Code. OSRD No. 5280. Research Report No. 18. U. S. Office of Scientific Research and Development, National Defense Research Committee, Applied Psychology Panel, Yerkes Lab. of Primate Biology, Orange Park, Fla. June 19, 1945.

15-106 Lindsley, D. B., Anderson, I. H., Baldwin, A. L., et al, Experiments in Training Radar Operators in Visual Code Reception. OSRD No. 4811. Research Report No. 16. U. S. Office of Scientific Research and Development, National Defense Research Committee, Applied Psychology Panel, Yerkes Lab. of Primate Biology, Orange Park, Fla. March 20, 1945.

15-107 Lindsley, D. B., Anderson, I. H., Baldwin, A. L., et al, The Effect of Extraneous Illumination upon Detection of Signals on an A-Scan Oscilloscope. OSRD No. 1264. Research Report No. 13. U. S. Office of Scientific Research and Development, National Defense Research Committee, Applied Psychology Panel, Yerkes Lab. of Primate Biology, Orange Park, Fla. October 18, 1944.

15-108 Lindsley, D. B., Anderson, I. H., Bridgman, C. S., et al, Visual Status of ASV Radar Operators. OSRD No. 3443. Project SC-70, NS-146. Research Report No. 9. U. S. Office of Scientific Research and Development, National Defense Research Committee, Yerkes Lab. of Primate Biology, Orange Park, Fla. March 20, 1944.

15-109 Lindsley, D. B., Anderson, I. H., Bridgman, C. S., et al, Vision as Related to Proficiency in Oscilloscope Operation. OSRD No. 3409. Project SC-70, NS-146. Research Report No. 8. U. S. Office of Scientific Research and Development, National Defense Research Committee, Yerkes Lab. of Primate Biology, Orange Park, Fla. February 24, 1944.

15-110 Lindsley, D. B., Anderson, I. H., Bridgman, C. S., et al, Radar Operator "Fatigue": The Effect of Length and Repetition of Operating Periods on Efficiency of Performance. OSRD No. 3334. Research Report No. 6. U. S. Office of Scientific Research and Development, National Defense Research Committee, Yerkes Lab. of Primate Biology, Orange Park, Fla. January 4, 1944.

15-111 Lindsley, D. B., Anderson, I. H., Bridgman, C. S., et al, Effect of Oscilloscope Operation on Vision. OSRD No. 2051. Project SC-70, NS-146. Research Report No. 4. U. S. Office of Scientific Research and Development, National Defense Research Committee, Yerkes Lab. of Primate Biology, Orange Park, Fla. November 15, 1943.

15-112 Lowery, E. A., and Brown, Fred R., Instrument Lighting - Investigations of Ultra-Violet Reflections. Part 3. A Study of Dark Adaptation during Observation of an Ultra-Violet Activated Aircraft Instrument Panel. Report TED NAM 51334. Part 3. Aeronautical Medical Equipment Lab., Naval Air Materiel Center, U. S. Naval Air Experimental Station, Philadelphia, Pa. April 28, 1950.

15-113 Mackworth, J. F., and Mackworth, N. H., Signal Overlap in Multichannel Displays. Great Britain. A.P.U. 226/54. Applied Psychology Research Unit, Medical Research Council, Cambridge, England.

15-114 Mackworth, N. H., Notes on the Clock Test - A New Approach to the Study of Prolonged Visual Perception to Find the Optimum Length of Watch for Radar Operators. Great Britain. Report No. 586. Flying Personnel Research Committee. May 1944.

15-115 MacLeod, S., and Bartlett, Neil R., "Human Reaction Time during Dark Adaptation." J. Opt. Soc. Amer. Vol. 44. May 1954. pp. 374-379.

15-116 McLaughlin, S. C., Jr., The Effect of Red Light on the Absolute Visual Threshold. Research Report. Project NM 001059.38.02. Naval School of Aviation Medicine, Pensacola, Fla. August 1953.

15-117 McLaughlin, S. C., Jr., Red Light Photosensitization: A Review of the Evidence. U. S. Naval School of Aviation Medicine, Pensacola, Fla. 1953.

15-118 Miles, Walter R., "Light Sensitivity and Form Perception in Dark Adaptation." J. Opt. Soc. Amer. Vol. 43. July 1953. pp. 560-566.

15-119 Mitchell, R. T., The Effect of Low Color Temperature Illumination and Red Illumination upon Subsequent Dark Adaptation. Vol. 8. pp. 27-38. Medical Research Lab., U. S. Naval Submarine Base, New London, Conn. 1949.

15-120 Mitchell, R. T., and Liaudansky, L. H., "Effect of Differential Adaptation of the Eyes upon Threshold Sensitivity." J. Opt. Soc. Amer. Vol. 45. No. 10. October 1955. pp. 831-834.

15-121 Peterson, G. E., "Design of Visible Speech Devices." J. Acoust. Soc. Amer. Vol. 26. 1954. pp. 406-413.

15-122 Pollack, Irwin, and Klemmer, E. T., Visual Noise Filtering by the Human Operator. II. Linear Dot Patterns in Noise. Tech. Report No. 54-15. Air Force Cambridge Research Center, Operational Applications Lab., Air Research and Development Command, Bolling Air Force Base, Washington, D. C. July 1954.

15-123 Potter, Ralph K., Kopp, George A., and Green, Harriet C., Visible Speech. Basement Study Hall and Angell Study Hall. 808 21 P869v. University of Michigan. 1947.

15-124 Reed, J. B., The Speed and Accuracy of Discriminating Differences in Hue, Brilliance, Area, and Shape. Project 20-L-2. Tech. Report No. SDC-131-1-2. Office of Naval Research, Special Devices Center, Port Washington, N. Y. September 1951.

15-125 Reed, J. B., and Bartlett, N. R., Tech. Report No. SDC-166-I-29. Office of Naval Research, Special Devices Center, Port Washington, N. Y. November 1, 1947.

15-126 Reed, J. B., and Wiener, A., The Speed and Accuracy of Discriminating Differences in Single and Compound Aspects of Vision. Tech. Report No. SDC-131-1-4. Office of Naval Research, Special Devices Center, Port Washington, N. Y. September 1952.

15-127 Rock, M. L., Annotated Bibliography on Visual Performance at Low Photopic Illumination Levels. USAF Tech. Report No. 5822. Air Materiel Command, Wright-Patterson Air Force Base, Ohio. May 1949.

15-128 Saltzman, I. J., and Garner, W. R., The Effect of Size and Brightness of the Speed of Identifying Number of Range Rings. Tech. Report No. SDC-155-1-79. Office of Naval Research, Special Devices Center, Port Washington, N. Y. January 20, 1949.

15-129 Sandberg, K. O. W., and Lipshultz, H. L., Tech. Report No. SDC-166-I-17. Office of Naval Research, Special Devices Center, Port Washington, N. Y. July 20, 1947.

15-130 Sanderson, J. A., and Tousey, R., Report No. H-2199. U. S. Naval Research Lab. November 26, 1943.

15-131 Schafer, T. H., and Shewmaker, C. A., A Comparative Study of the Audio, Visual, and Audio-Visual Recognition Differentials for Pulses Masked by Random Noise. Report No. 372. U. S. Navy Electronics Lab. May 1, 1953.

15-132 Simonson, Ernst, Blankstein, Samuel S., and Carey, Eben J., "The Relationship between Light Adaptation and Dark Adaptation and its Significance for Appraisal of the Glare Effect of Different Illuminants." Amer. J. Ophthal. Vol. 29. 1946. pp. 328-340.

15-133 Simonson, Ernst, and Brozek, Josef, "Work, Vision and Illumination." Illum. Engng. Vol. 47. 1952. pp. 335-349.

15-134 Sinden, R. H., "Some Consequences of the Additivity of Luminosities." J. Opt. Soc. Amer. Vol. 40. October 1950. pp. 647-652.

15-135 Sleight, Robert B., "The Relative Discriminability of Several Geometric Forms." J. Exp. Psychol. Vol. 43. April 1952. pp. 324-328.

15-136 Smith, S. W., and Dimmick, F. L., "The Facilitative Effect of Red Light on Dark Adaptation." J. Opt. Soc. Amer. Vol. 43. 1953. p. 541.

15-137 Smith, Stanley W., Morris, A., and Dimmick, Forrest L., "Effects of Exposure to Various Red Lights upon Subsequent Dark Adaptation Measured by the Method of Constant Stimuli." J. Opt. Soc. Amer. Vol. 45. No. 7. 1955. pp. 502-506.

15-138 Smith, N. P. E., and Ruffell, H. P., The Design and Display of Pilots' Instruments. Great Britain. Report No. 692. Flying Personnel Research Committee.

15-139 Spencer, J., A Comparison of an Auditory Warning System with a Controlled Visual Warning System for Use in Aircraft. Great Britain. Report No. 818. Flying Personnel Research Committee. March 1953.

15-140 Sperling, Harry G., and Farnsworth, Dean, The Discrimination of Color. I. An Experimental Evaluation of Four Methods for Measuring the Difference Limen of Chromaticity. Report No. 154. Vol. 9. 1950. pp. 54-89. Medical Research Lab. BuMed Project NM 003 041.19.01. U. S. Naval Submarine Base, New London, Conn. September 15, 1950.

15-141 Sweet, A. L., and Morgan, C. T., Tech. Report No. SDC 166-I-25. Office of Naval Research, Special Devices Center, Port Washington, N. Y. July 10, 1947.

15-142 Thomson, L. C., and Trezona, P. W., "The Variations of Hue Discrimination with Change of Luminance Level." J. Physiol. Vol. 114. No. 1 and 2. 1951. pp. 98-106.

15-143 Tinker, Miles A., "Interpretation of Illumination Data." Amer. J. Optom. and Arch. Amer. Acad. Optom. Vol. 29. 1952. pp. 293-300.

15-144 Tinker, Miles A., "The Effect of Intensity of Illumination upon Speed of Reading Six Point Italic Print." Amer. J. Psychol. Vol. 65. October 1952. pp. 600-602.

15-145 Tinker, Miles A., "Derived Illumination Specifications." J. Appl. Psychol. Vol. 35. December 1951. pp. 377-380.

15-146 Tinker, Miles A., "Lighting and Color." Chapter 17 in Human Factors in Undersea Warfare. U. S. National Research Council, Washington, D. C. 1949.

15-147 Tower, Walter R., "Radar '3-D' Indicators - A Stereoscopic Solution." Sperry Engineering Review No. 2. Vol. 7. March-April, 1954. pp. 2-10.

15-148 Uhlaner, J. E., Gordon, D., Woods, I., and Zeidner, J., A Pilot Study of the Relationship between Scotopic Visual Acuity and Acuity at Photopic and Mesopic Brightness Levels. PRS Report No. 963. Department of the Army, TAGO, Personnel Research Sect., Washington, D. C. July 1952.

15-149 Van Saun, H. R., The Comparative Interpretability of Two Methods of Presenting Bombing Information by Radar. TSEAA-694-5. Air Materiel Command, Aero Medical Lab., Engineering Div., Wright-Patterson Air Force Base, Ohio. October 1946.

15-150 Vernon, M. D., Scale and Dial Reading. Great Britain. A.P.U. 49. Medical Research Council, Applied Psychology Research Unit, Cambridge, England. June 1946.

15-151 Verplanck, Wm. S., "Visual Communication." Chapter 12 in Human Factors in Undersea Warfare. U. S. National Research Council, Washington, D. C. 1949.

15-152 Wagner, Henry G., Report on Study of Red Lighting Requirements for the Cockpits of Naval Aircraft. Report TED NAM 31410. Aeronautical Medical Equipment Lab., Naval Air Materiel Center, U. S. Naval Air Experimental Station, Philadelphia, Pa. March 4. 1947.

15-153 Warrick, M. J., Counters for Airborne Use. WADC Tech. Report 54-266. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. June 1954.

15-154 Warrick, M. J., Design and Use of Counters for Airborne Equipment. Tech. Note WCRD 52-80. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. October 1952.

15-155 Weinbach, A. P., Lee, R. H., Jones, Benjamin F., and Bracket, F. S., Preliminary Report on the Influence of Brightness and Color of Pre-adapting Lights on the Course of Dark Adaptation. U. S. National Institute of Health, Div. of Industrial Hygiene. January 5, 1942.

15-156 Weitz, Joseph, Effect of Shape and Color Coding of Airplane Controls on Speed and Accuracy of Performance. Project No. 336. Report No. 1. USAF School of Aviation Medicine, Randolph Field, Texas. December 23, 1944.

15-157 White, William J., and Sauer, Shirley C., Scale Design for Reading at Low Brightness. WADC Tech. Report 53-464. Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. March 1954.

15-158 Williams, S. B., Operator Efficiency as a Function of Scope Size. Contract AF 30(602) 578. Progress Report No. 1. William and Mary College, Williamsburg, Va. June 1-September 1, 1953.

15-159 Williams, S. B., Visibility on Radar Scopes. Tech. Report No. SDC 166-I-82. Office of Naval Research, Special Devices Center, Port Washington, N. Y. February 15, 1949.

15-160 Williams, S. B., "Visibility on Cathode-Ray Tube Screens: Viewing Angle." J. Opt. Soc. Amer. Vol. 39. 1949. pp. 732-785.

15-161 Williams, S. B., The Search Factor in Detecting Weak Radar Targets. Tech. Report No. SDC [illegible]-I-28. Office of Naval Research, Special Devices Center, Port Washington, N.Y. July 1947.

15-162 Williams, S. B., and Hames, R. M., Tech. Report No. SDC 166-I-7. Office of Naval Research, Special Devices Center, Port Washington, N. Y. January 10, 1947.

15-163 Williams, S. B., and King, Ellwood, The Effect of CRT Bias on Visibility of Targets on a Remote PPI. Tech. Report No. SDC 166-I-6. Office of Naval Research, Special Devices Center, Port Washington, N. Y. December 10, 1946.

15-164 Wilson, Mathew R., Red-Green Filters for Simulated Instrument Flying. Project 21-1207-0003. USAF School of Aviation Medicine, Randolph Field, Texas. December 1952.

15-165 Wolf, E., "Effects of Exposure to Ultra-Violet Light on Subsequent Dark Adaptation." Proc. Nat. Acad. Sci. Vol. 31. November 1945. pp. 349-355.

15-166 Wolf, Ernst, "Effects of Exposure to Ultra-Violet Light on Human Dark Adaptation." Proc. Nat. Acad. Sci. Vol. 32. No. 8. 1946. pp. 219-228.

GLOSSARY

aberration of light - the passage of light by paths other than those making for the efficiency of an optical system (including that of the eye), and exclusive of the effect of poor adjustment of focus.

accommodation - the process by which the lens of the eye adjusts to objects at different distances by changing its curvature so that the image is focused on the retina.

achromatic - lacking in hue and saturation. Achromatic colors vary only in brightness, from black to white.

acuity, visual - the ability of the eye to perceive form and detail in a plane perpendicular to the line of sight.

adaptation - a change in sensitivity to a stimulus following continuous exposure to the same stimulus.

adaptometer - any device for measuring the course or degree of sensory adaptation, in terms of fall or rise of threshold or sensitivity.

additive color mixture - type of color mixing in which the colors, that are mixed, all stimulate the same retinal elements. This can be accomplished by viewing overlapping light beams projected on the same surface.

AGCA - "automatic ground-controlled approach."

ambient (illumination) - encompassing on all sides.

ambinocular field - the total area that can be seen by either eye; it is not limited to the binocular field but includes, in addition, monocular regions visible to the right eye but not to the left, and vice versa.

ametropia - a general term embracing any sort of regular refractive defect in the eye.

analysis of variance - a method for analyzing the total variance in a set of measurements into its component variances or parts which may be attributed to varying experimental factors.

anisometropia - unequal refractive power in the two eyes.

aphakia - absence of the crystalline lens.

aqueous humor - a transparent, watery fluid, which fills the space between the cornea and the lens in the anterior part of the eye.

A-scope - a radarscope that presents the target range by a vertical deflection of the time base, or, in certain modified versions, by a horizontal deflection.

asthenopia - tired or fatigued feeling of the eyes, usually expressed by a burning or itching sensation in the eyes and occasionally accompanied by a low, frontal headache.

astigmatism - defect of the eye. Two types are recognized: regular, in which the error is due to a greater curvature of a refractive surface (chiefly the cornea) in one meridian, and which may be correct by a cylindrical lens; and irregular, in which the refraction is irregularly unequal within the pupillary area and which is not correctable except by contact lenses.

attenuation - the decrease of an electrical signal; the process of decreasing the power of an electrical signal.

attitude - the aspect that an aircraft presents at any given moment, as determined by its inclinations about its three axes. Also attributively, as in attitude indicator, attitude instrument.

aural signal - a signal which must be heard by the ear and be interpreted without benefit of visual instruments.

azimuth - bearing in the horizontal plane, usually expressed as an angle, and in air navigation measured clockwise from true north, grid north, or magnetic north, from 0° to 360°.

bias - the direct-current voltage between two elements of a vacuum tube: grid bias.

binocular field - the field of vision of the two eyes acting conjointly.

blind spot - a small area in the retina, where the optic nerve leaves the eyeball. The blind spot is not sensitive to light stimulation.

brightness - 1. attribute of visual sensation determined by intensity of light radiation reaching the eye. Sometimes called lightness, tint, or value. Refers to variations along the achromatic scale of black to white. 2. photometric measure of light emission per unit area of a luminous body or of a translucent or reflective surface, i.e., candlepower per unit area.

BuAer - "Bureau of Aeronautics." A Navy bureau created in 1921, charged with matters pertaining to naval aeronautics as may be prescribed by the Secretary of the Navy. The Bureau of Aeronautics has the responsibility of designing, procuring, and maintaining Navy aircraft and aviation equipment.

candle - unit of light intensity. At a distance of one foot, one candle produces an illumination of one foot-candle (equivalent to one lumen per square foot) upon a surface normal to the beam.

cathode-ray indicator - a cathode-ray tube with a calibrated screen to indicate position.

cathode-ray screen - the luminescent screen of a cathode-ray oscilloscope or tube, which receives the cathode-ray beam.

cathode-ray tube (CRT) - a vacuum tube in which the deflection of an electron beam indicates on a fluorescent screen instantaneous values of the actuating voltages or currents.

CAVU - [Pronounced as a word] "ceiling and visibility unlimited."

chiasma - the junction point of the optic nerves, from which they again diverge and pass to the respective cerebral hemispheres. In the human eye, the fibers from the nasal half of each retina cross at this point, the remainder going to the hemisphere on the same side.

choroid - the intermediate of the three layers of the eyeball, situated between the sclera and the retina.

chroma - synonym for color saturation.

ciliary body - an annular mass of unstriped muscle fibers, which surrounds the eye-lens and regulates its curvature, thereby accommodating (focusing) the eye for vision at various distances.

color - visual sensation determined by interaction of wavelength, intensity, and mixture of wavelengths of light. The corresponding attributes of color are hue, brightness, and saturation.

colorimetry - a method for measuring colors and specifying them in numerical or definite symbolic terms.

complementary color - color which, when combined with another color, and acting together with it on the retina, cancels out the hue and saturation of the second color, so that the total effect of the combination matches an achromatic stimulus, giving a white or gray sensation.

cones - structures found in the retina of the eye that constitute specific receptors for vision at high levels of illumination and for color vision.

contrast - difference in brightness between two portions of visual field, usually expressed in experimental procedure as

$$C = \frac{B_{background} - B_{test\ field}}{B_{background}} \times 100\%.$$

Also, change in apparent brightness of color of a visual field as a result of recent stimulation of this field or a neighboring one; effect is to enhance opposing characteristics.

convergence - the turning of the two eyes toward each other so that their respective lines of sight meet at a point in space. Thus, the image is formed at corresponding regions of the two retinas.

cornea - the transparent portion of the outer coat of the eyeball, situated in front of the iris and constituting the first of the refractive media of the eye.

correlation - the tendency of certain paired measures to vary concomitantly, so that knowledge of the value of one measure gives information as to the mean value of all measures paired with that measure.

critical ratio - a statistically determined number that indicates the significance of the change in results obtained by varying an experimental condition. If CR = 3 or more, there is practically no chance that the difference obtained could be obtained by chance variation alone.

CRT - "cathode-ray tube."

cues - stimuli which guide the organism's responses, e. g., highlights and shadows in depth perception. Sometimes referred to as clues.

dark adaptation - process whereby the eye attains greater sensitivity to light placed in an illumination lower than that to which it was previously exposed.

decibel - log unit expressing relative levels of intensity or power.

diffraction - bending of a portion of the wave-front behind the edge of an obstacle.

diopter - measurement of the focusing power of a lens according to the reciprocal of the focal length of the lens. A lens of one diopter focuses parallel rays at 1 meter.

diplopia - any condition of the ocular mechanism in which a single external object is seen double.

divergence - the turning of the two eyeballs outward with respect to each other, or their movement from a position of greater convergence to one of less.

ECM - 1. "electronic countermeasure(s)." 2. "electronic countermeasure mission."

emmetropic - the normal condition of the ocular refractive system, in which rays from distant objects are focused sharply on the retina of the eye, while accommodation is relaxed.

extrafoveal - outside of the fovea.

fixation point - point in the visual field at which the observer is looking directly. It is the point whose image falls on the center of the fovea.

flicker, visual - a rapid periodic change in a visual impression, due to a corresponding rapid cyclic change in the intensity or some other characteristic of the stimulus.

flight simulator - a device that simulates any or all of the conditions of actual flight, used especially for training purposes; specifically, any ground trainer. In a broad sense, the term "flight simulator" could be applied to a centrifuge or to a low-pressure chamber.

focal length - a characteristic of a lens or other focusing optical system, being the focal distance for parallel entering rays.

fovea - a small depression in the central region of the retina, containing only cones.

g - standard unit of acceleration. 1 g is the acceleration due to gravity (32 ft/sec^2). g is often used to represent the force on the body due to acceleration. By convention, positive g is the force that drives the blood from the head to the foot (as in a pilot pulling out of a dive); negative g is the force that drives the blood from the foot to the head; transverse g is the force that acts on the body from front to back or vice versa.

GCA - "ground-controlled approach." Also attributively, as in GCA controller, GCA equipment, GCA landing, GCA weather, etc.

GCI - "ground-controlled interception."

gyro horizon - 1. an artificial horizon. 2. a flight indicator.

heterophoria - the tendency of either eye to deviate abnormally from its position of fixation when fusion of the two images is prevented; muscular imbalance.

heterotropia - the failure of one of the two eyes to take its proper position of binocular fixation with reference to the other, due to defect or lack of control of the extrinsic ocular muscles.

hue - the attribute of color determined primarily by the wavelength of light entering the eye. Spectral hues range from red through orange, yellow, green, and blue to violet.

hyperopia - synonym for farsightedness; a defect of the eye such that, with accommodation relaxed, parallel rays of light focus behind the retina.

hypoxia - oxygen deficiency in the body tissues.

IFF - "identification, friend or foe."

ILAS - "instrument low approach system."

illuminance - the flux striking a surface, measured in lumens per unit area.

illusion - a misinterpretation of certain elements in a given experience, so that the experience does not represent the objective situation.

ILS - "instrument landing system."

intensity - 1. the quantitative attribute or value of a sensory process or unit, correlated in general with the intensity of the physical stimulus. 2. flux per solid angle from a point source measured in lumens per steradian.

inverse square law - illumination varies inversely as the square of the distance of receiving plane from point source:

$$E = \frac{I}{d^2} \quad \text{where } E = \text{illumination in foot-candles}, \; I = \text{source intensity in candles}, \; d = \text{distance in feet.}$$

iris - a flat, ring-shaped structure situated within the eyeball immediately in front of the lens, containing unstriped muscle-fibers whose contraction and relaxation regulate the amount of light admitted through the pupil.

isopter - all the points at which a threshold level of performance is obtained, plotted on a chart of the visual field so that they form an irregular ring around the center of vision.

just noticeable difference (jnd) - a difference limen. The least amount of a stimulus which, added to or subtracted from a standard stimulus, produces a just noticeably different experience.

keratoconus - conically bulging cornea.

lambert - unit of brightness; it is the brightness of a perfect diffusing surface giving out one lumen per square centimeter of surface area.

Landolt ring - a ring with a small gap at one point, used to test visual acuity by having observer report orientation of the gap.

lens - the transparent body, convex on its front and back surfaces, situated just behind the iris and pupil of the eye; it serves, through changes in its shape brought about by the action of the ciliary muscles, to focus the eye for different distances.

light - radiant energy that arouses visual sensations.

LSO - "landing signal officer."

lumen - unit of luminous flux; luminous flux emitted per second by a point source of one candle intensity through a solid angle of one steradian.

luminance - the luminous emittance in one direction from an extended source, measured in lumens per unit area per steradian.

luminous emittance - the flux emitted in all directions from each unit area of an extended source, measured in lumens per unit area.

luminous flux - analagous to rate of transfer of energy, it is the total visible energy emitted by a source per unit time.

mean - one common measure of central tendency.

$$M = \frac{\sum X}{N}$$

where: M = mean of a set of numerical values
X = individual value in set
N = number of numerical values in set.

median - the middlemost of a set of values; the value above which and below which 50% of the values fall.

meniscus - a lens, one of whose refracting surfaces is convex and the other concave.

method of average error - the psychophysical method in which the subject manipulates the variable stimulus until he judges it to match the standard. The error is then measured.

method of constant stimuli - psychophysical method in which the frequency with which a sensation occurs is measured as a function of the variation in magnitude of the stimulus. A few discrete stimuli are used and each is presented many times.

method of limits - method of investigation which proceeds by gradually decreasing the value of a given stimulus (or the difference between two stimuli) until it is no longer noticeable; and also by increasing the stimulus value (or the difference between two stimuli) from a definitely imperceptible value until it becomes just noticeable.

method of paired comparison - method in which each member of a series is compared with every other member with respect to a given characteristic.

minimum distinguishable acuity - least change in form that can be identified visually, i.e., the least lateral displacement in the ends of two lines that will result in the experience of discontinuity. It is measured in terms of the angle subtended by the object, measured at the eye.

minimum perceptible acuity - smallest object that is visible. It is measured in terms of the angle subtended by the object, measured at the eye.

minimum separable acuity - smallest space between two lines that can be discriminated as a gap. It is measured in terms of the angle subtended by the gap, measured at the eye.

minimum visible acuity - least area of a uniform brightness that can activate the eye. It is measured in terms of the angle subtended by the area, measured at the eye.

mode - a measure of central tendency. It is the score occurring in the largest number of cases.

monocular field - field of vision with one eye alone.

motion parallax - the apparent difference in rate of movement of two objects actually moving at the same velocity but at different distances from the observer.

MTI - "moving target indicator."

myopia - refractive defect of certain eyes so that, with the lens relaxed, parallel rays of light are brought to a focus before they reach the retina.

nomograph - a chart consisting of three (or more) scales, which represent values of related variables; given the values of two of these variables, one can determine the value of the third related variable from the chart.

omnibearing - a bearing toward an omnidirectional radio-range station, as given to an aircraft by the omnidirectional radio range.

omnirange - short for "omnidirectional radio range."

ONR - "Office of Naval Research."

optic disc - a small, low eminence on the inner surface of the retina, within the eyeball, formed by the nerve-fibers of the retina, as they collect just before emerging from the eyeball to form the optic nerve.

optic nerve - the second cranial nerve, which connects the retina of the eye with the visual centers.

orthophoria - condition in which an eye may continue to look toward an object even if the object is hidden.

orthorater - commercial apparatus for determining visual acuity at both near and far accommodations, but with distance factor induced by a system of lenticular prisms.

parallactic angle - the angle between the two lines drawn from a single point on an object to the two eyes.

parameter - 1. a constant having a series of particular and arbitrary values, each value characterizing a member in a system or family of expressions, curves, surfaces, functions, or the like. 2. in psychological use, a criterion that has shifting values.

perception - the awareness of external objects, qualities, or relations, which ensues directly upon sensory processes.

perimeter - an instrument for determining the discriminative powers of different parts of the retina.

phosphor - a substance applied to the inner face of a cathode-ray tube which fluoresces during bombardment by electrons, and phosphoresces after bombardment.

photometer - an optical device that utilizes equations of brilliance to permit the measurement of a photometric quantity, such as candle power, illumination, or brightness.

photometry - the measurement of visible radiation on the basis of its effect upon the eye under standard conditions, and usually involving an adjustment of two contiguous parts of the visual field, either to identify or to determine a minimal difference.

photopic - vision under illumination sufficient to permit the discrimination of colors. Sometimes called daylight vision.

pip - 1. a blip. 2. an artificial signal on a radarscope, similar to a blip, used for reference. 3. in gunnery, a pipper.

pipper - a small hole in the reticle of an optical sight or computing sight; a pipper image.

PPI - "plan-position indicator." Also attributively, as in PPI operator, PPI photo, PPI scan, PPI scope, etc.

presbyopia - a condition of the eye characterized by ability to see distant objects clearly and inability to obtain a clear picture of nearby objects, due to inelasticity of the lens, with consequent reduction of accommodation, which develops with advancing age.

probable error - range of scores obtained by the middle 50% of a group. (PE = 0.6745SD)

GLOSSARY (Cont)

pseudo-isochromatic test - color-blindness test in which the plates contain two colors which can be distinguished by the normal eye, but not by the color-blind.

psychophysical methods - standarized procedures for presenting stimulus material to subject for judging and for recording his results. Originally developed for determining functional relations between physical stimuli and correlated sensory responses, but now used more widely.

pupil - the circular opening in the iris, which forms the diaphragm of the optical system of the eye, regulating the amount of light admitted to the eye by contracting as the light increases, or the reverse.

radarscope - the cathode-ray oscilloscope or screen in a radar set.

radarscope display - the visual presentation or picture displayed on a radar screen.

radar screen - 1. a radar net. 2. a cathode-ray screen in a radar set. See cathode-ray screen.

RCM - 1. "radar countermeasures." 2. "radio countermeasure."

reduced eye - a simple schematic system designed to have the same optical properties as the average unaccommodated human eye.

reflectance - ratio of luminous flux reflected from a surface to luminous flux striking it.

refraction - a change in the angle of propagation of a wave in passing from one medium to another of different density or elasticity.

refractive index - a numerical expression indicating the degree to which the path of light or radiant energy is bent in passing from one transparent medium into another.

response - the muscular contraction, glandular secretion, or any other activity of an organism which results from stimulation.

retina - inner coating of the eyeball, which receives the image formed by refraction of light rays at the cornea and lens; it is made up of rods and cones, the receptor cells for vision.

retinal disparity - the difference which exists between the images formed in the right and left eyes when a solid object is viewed binocularly.

rhodopsin - a substance found in the rods of the dark-adapted eye, which bleaches rapidly on exposure to light, and is believed to be the substance underlying scotopic or twilight vision.

RMI - "radio magnetic indicator."

rods - structures found in the retina of the eye which constitute specific receptors for vision at low levels of illumination. They do not produce sensations of color.

saccadic movements - sudden movement of the eyes from one fixation point to another.

saturation - extent to which a chromatic color differs from a gray of the same brightness, measured on an arbitrary scale from 0% to 100% (where 0% is gray).

sclera - the white outer fibrous coat of the eyeball, primarily a supporting or skeletal structure.

scotoma - a blind or partially blind area in the visual field.

GLOSSARY (Cont)

scotopic vision - vision which occurs in faint light, or after dark adaptation. Sometimes called twilight or night vision. Hues and saturations cannot be distinguished.

sensation - subjective response or any experience aroused by stimulation of a sense organ.

servo system - control system with feedback. The behavior of a servo is governed, not by the input signal alone, but by the difference between the input and some function of the output.

simulator - any machine or apparatus that simulates a desired condition or set of conditions, such as a flight simulator.

specular surface - one that scatters little of the flux striking it.

standard deviation - statistical term used to indicate the variability of scores or measurements.

$$SD = \sqrt{\frac{\sum (\text{deviation from mean})^2}{\text{number of trials}}}$$

statistically significant difference - a difference in the results obtained under two experimental conditions which can legitimately be concluded not to be due to chance; usually significant differences are arbitrarily considered to be differences that would be expected to occur by chance no more than 1% (or 5%) of the time.

stimulus - energy, external or internal, which excites a receptor.

subtractive color mixture - method of color mixture in which a beam of light is passed through two or more transparent colored filters in succession. Only those wavelengths which are common to both or all will be transmitted. By this method, white light passing through broad band yellow and blue filters gives green.

TacAN - "tactical air navigation."

threshold - a just barely noticeable environmental energy level (absolute threshold) or energy change (differential threshold).

traffic pattern - a pattern in the air above or about an airdrome, which is normally followed under visual conditions either by aircraft prior to touchdown or by aircraft after takeoff.

transillumination - the passing of light through media or material for purposes of increasing its "readability," an organ of the body for medical examination.

transmittance - ratio of transmitted to incident luminous flux (expressed as percent).

troland - unit of retinal illuminance equal to that produced by viewing a surface whose luminance is 1 candle per square meter through an artificial pupil whose area is 1 square millimeter centered on the natural pupil.

value - synonym for brightness.

vertigo - dizziness or giddiness, especially as brought on by airsickness.

VFR - "visual flight rules." Also attributively, as in VFR conditions, VFR flight, VFR traffic. Used adverbially, as in "we will fly VFR."

visual angle - the angle subtended by an object of vision at the nodal point of the eye. The magnitude of this angle determines the size of the corresponding retinal image, irrespective of the size or distance of the object.

visual field - that part of space that can be seen when head and eyes are motionless, (or) the totality of visual stimuli which act upon the unmoving eye at a given moment.

vitreous humor - the transparent, jelly-like mass which fills the eyeball from the concave surface of the retina as far forward as the lens.

VOR - "VHF omnidirectional range."

wavelength - the distance in meters traveled by an electromagnetic wave during the interval covered by a cycle.

whiteout - an atmospheric and surface condition in the arctic in which no object casts a shadow, the horizon being indiscernible, and only very dark objects being seen. Also called "milky weather." (This condition is brought on when snow cover is complete and the clouds so thick and uniform that light reflected by the snow is of about the same intensity as the light of the sun after passing through the clouds.)

windscreen - [British] a windshield.

windshield - anything that serves to shield against wind; on an airplane, a pane or surface area of glass or other transparent material ahead of the cockpit or in front of the pilot's cabin affording protection from the wind and allowing forward vision.

World Aeronautical Chart (WAC) - one of a series of aeronautical charts covering the entire world, designed for use in land-mark navigation, radio navigation, dead reckoning, and celestial navigation.

Zero Reader - [Trade name] a gyroscopic instrument that combines the functions of gyro horizon, directional gyro, magnetic compass, sensitive altimeter, and cross-pointer indicator.

zonule fibers - the set of bands which extend from the ciliary body to the equator of the lens of the eye, constituting its suspensory ligament.

INDEX

INDEX (Cont)